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HYDROGEOLOGIC FACTORS TO BE ADDRESSED IN DISPOSAL GUIDELINES

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ABSTRACT

This report identifies the physical hydrogeologic factors that should be addressed for performance assessment of a radioactive waste disposal facility in plutonic rock. The hydrogeologic factors include theoretical methods, groundwater flow factors and solute transport parameters. Theoretical methods, including different deterministic and stochastic approaches for evaluating physical hydrogeologic conditions, are evaluated with respect to data requirements, applications and limitations. Preferred methods for measurement and determination of the identified groundwater flow factors and solute transport parameters are discussed. A recommended set of procedures for reliable hydrogeologic characterization of a plutonic rock mass at both regional and site scales is also presented.

RÉSUMÉ

Le présent rapport identifie les facteurs hydrogéologiques physiques dont nous devrions tenir compte dans l'évaluation de la qualité d'un dépotoir de déchets radioactifs aménagé dans un massif plutonique. Ces facteurs hydrogéologiques englobent les méthodes théoriques, les facteurs relatifs à l'écoulement des eaux souterraines et les paramètres du transport des solutés. Les méthodes théoriques, y compris diverses méthodes déterministes et stochastiques d'évaluation des conditions hydrogéologiques physiques, sont évaluées en tenant compte des besoins en données, de leurs applications et de leurs limites. Nous traitons des meilleures méthodes de mesure et de détermination des facteurs relatifs à l'écoulement des eaux souterraines et des paramètres du transport des solutés qui ont été identifiés. Nous présentons en outre une série de mesures recommandées pour une caractérisation hydrogéologique fiable d'un massif plutonique à l'échelle régionale et locale.

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1. INTRODUCTION

1.1 BACKGROUND

In many countries, geologic formations are under consideration as disposal mediums for high-level radioactive wastes. In Canada, current plans call for the wastes to be emplaced in a repository deep in plutonic bedrock. It will be necessary for regulatory purposes, to demonstrate the impact of a nuclear waste repository on the accessible environment. Regulatory guidelines are needed to guide an applicant in acquiring and interpreting sufficient relevant information to show the Atomic Energy Control Board that the conditions addressed by the guidelines are suitable for disposal. This evaluation will likely be in the form of an assessment or quantitative prediction of the long term performance of the radioactive waste isolation system after the waste has been emplaced and the repository has been closed.

The most likely, and perhaps only, mechanism by which radionuclides may reach the accessible environment is through the dissolution and leaching of the wastes by groundwater and subsequent movement of dissolved radionuclides by the groundwater flow system. Assessment of the risk posed by this potential pathway requires an understanding of the groundwater flow and solute transport characteristics of the geologic environment under consideration. This understanding can only be achieved through thorough investigation and evaluation of the hydrogeologic parameters or factors that control groundwater flow and solute transport in fractured plutonic rocks at site, local and regional scales. Because of the importance of this potential pathway, the Atomic Energy Control Board has commissioned this study to ensure that regulatory guidelines on hydrogeologic conditions are as appropriate and complete as possible.

1.2 OBJECTIVES AND SCOPE

The overall objectives of this study are twofold:

- to identify the primary hydrogeologic parameters that should be investigated in order to evaluate near surface and subsurface hydrogeologic systems for deep disposal of radioactive waste in plutonic rock, and

- to identify and evaluate the appropriate theoretical approaches, scales of study, test methods and test equipment for determining the primary physical hydrogeologic parameters.

To accomplish these objectives, the study is divided into three sections. These sections are:

- Theoretical methods for evaluating hydrogeologic conditions;

- Hydrogeologic factors to be addressed in disposal guidelines and;

- Investigation procedures for hydrogeologic characterization.

In this study only physical hydrogeologic parameters and the theoretical and practical methods for evaluating them are discussed. Geochemical parameters, such as the chemical and isotopic composition of groundwater, bedrock and fracture infilling materials, and waste form compatibility with in situ groundwaters, are recognized as important factors that must also be addressed in a comprehensive evaluation of surface and subsurface water systems for deep disposal of radioactive waste in plutonic rocks, but a discussion of geochemical

aspects is beyond the scope of this study. Nonetheless, it should be noted that chemical and isotopic data can provide important information on the potential geochemical mobility of radionuclides leached from the solid waste forms as well as information on the likely age, origin and geochemical evolution of groundwaters. Furthermore, in low permeability materials such as plutonic rock, flow system interpretation using classic hydraulic analyses may be difficult and isotopic and geochemical techniques will likely be required to assess the groundwater flow conditions.

In the theoretical methods section, the different theoretical and conceptual approaches for evaluating the physical hydrogeologic conditions of fractured plutonic rocks have been identified and reviewed. These include, for instance, equivalent porous media, dual porosity and fracture network conceptual approaches for use with both deterministic and stochastic methods in evaluating groundwater flow and solute transport characteristics. The evaluation of different theoretical approaches focusses on data requirements, application to different areal and temporal scales and limitations. In discussing the different theoretical methods, the simple physical laws and material balance considerations that form the basis of the partial differential equations governing fluid flow and solute transport in geologic media are introduced. The governing physical equations provide a convenient framework to identify and tie together the primary hydrogeologic parameters that should be investigated. Furthermore, the governing equations form the basis for simulation models which will likely be used in performance assessments of a nuclear waste repository in plutonic rock.

In the hydrogeologic factors sections, the primary physical hydrogeologic parameters controlling fluid flow and solute transport are identified. In addition to the primary hydrogeologic factors such as permeability, flow porosity and fluid potential, secondary parameters that may influence these parameters are identified; for

example, in the case of hydraulic conductivities this may include fluid properties such as density and viscosity, fracture characteristics and state of stress. For each primary hydrogeologic parameter we also assess why it is important, at what scale it should be measured, how it can be measured and what methods and techniques are most suited to its reliable measurement.

In the final section of the report, a step-by-step sequence of investigation procedures for obtaining, at relevant scales, the hydrogeologic parameters necessary for performance assessment of a nuclear waste repository is described. Methods of checking the reliability, reproducibility and representativeness of the data are included in this section.

1.3 IMPORTANCE OF SURFACE VERSUS SUBSURFACE WATER SYSTEMS

Radionuclides may be transported by groundwater from a repository to surface and subsequently by surface water systems. The relatively long transport times anticipated in subsurface water systems (as compared to those for surface water systems) is expected to provide the required isolation from the biosphere and allow for the decay of radioactive elements and daughters. As a result, subsurface water systems are recognized as a critical component of the overall hydrologic system. Furthermore, because of the expected slow rate of release of radionuclides from the geosphere to the biosphere, simple models may adequately describe the transport of radionuclides in surface water systems. For example, simple dilution or mixing cell models that assume instantaneous and complete mixing of radionuclides may be considered adequate to describe nonreactive transport in surface water systems such as rivers, lakes and watersheds.

The transient nature of the climatic and geomorphic processes that influence surface water characteristics over the time frames considered for the radioactive waste disposal problem (thousands to

hundreds of thousands of years) also tend to force the focus of geologic disposal on the hydrogeologic system. For example, climatic changes, such as changes in mean annual precipitation and temperature, can significantly modify the surface water system, both in the short term, through changes in the fluvial erosion rates and the extent and duration of permafrost conditions, and in the long term by continential glacial events.

For these reasons, the focus in performance assessment of geologic disposal is on the evaluation of the isolation capability provided by the geosphere. Therefore, in this report we consider only the hydrogeologic factors of the subsurface water systems. Surface water systems are considered only in the context of how they influence the groundwater systems, such as changes in the location and rates of groundwater recharge and discharge.

2. FACTORS TO BE ADDRESSED

The factors that should be considered in the hydrogeologic evaluation of candidate nuclear waste repository sites can be broadly described as pertaining to the movement of water and solute through the media. These factors typically fall into one of the following categories:

- Theoretical method (including deterministic and stochastic approaches);
- System boundary conditions - such as those that are used to define perimeter conditions of the system (including recharge);
- Primary parameters - those that are incorporated explicitly in the equation which forms the basis for the theoretical method used to describe the groundwater system (e.g., permeability, porosity, dispersion coefficients);
- Secondary parameters - those that are associated with secondary processes which through coupling may affect primary parameters (e.g., thermal expansivity, heat capacity).

Each of these factors may be subdivided into two categories, one dealing with groundwater flow processes, the other dealing with solute transport processes. Properties relating to the movement of solute through geologic media may be further classified as either geochemical or physical. Geochemical transport parameters pertain to processes, such as adsorption, ion exchange and chemical precipitation or dissolution describing the solutes' interactions with the geologic

media. Physical transport parameters are used to describe processes such as the advection of groundwater, mechanical dispersion and molecular diffusion of solute. Table 2.1 summarizes the hydrogeologic factors that should be addressed in disposal guidelines and that are subsequently discussed in this section.

In addition to evaluating those factors that define the primary parameters and boundary conditions of the region of concern, factors that define the internal geometry of the system should also be evaluated. In crystalline rock systems, this means the characterization of fracture properties such as:

- aperture - qualitatively measured with acoustic televiewer, T.V. logs, cores;
- length - from mapping;
- orientation - from mapping, oriented core, acoustic televiewer and TV logs;
- density/spacing - from acoustic televiewer, T.V. logs, cores, mapping;
- connectivity.

It should be stressed that the theory relating such specific fracture properties to reliable estimates of rock mass permeability does not currently exist. Fracture property information is, however, useful in defining flow paths and probability density functions of fracture attributes, for use in stochastic models.

2.1 THEORETICAL METHODS

In this section, the different theoretical methods and conceptual approaches for evaluating the hydrogeologic conditions of fractured plutonic rock are identified and discussed. As with the

Table 2.1 Summary of Primary Hydrogeologic Factors to be Addressed in Guidelines for the Deep Disposal of Radioactive Waste

Theoretical Method

- Deterministic
  - porous media or discrete fracture
- Stochastic
  - most promising since the concept of risk is inherent in methodology
  - techniques have not been perfected

Groundwater Flow Properties

- Flow system geometry and boundary conditions
  - strongly influenced by geologic and structural framework, topography, hydrology and paleohydrology
- Hydraulic conductivity
  - depends on fracture permeability and fluid properties
  - strongly influenced by structural framework, stress, and thermomechanical effects
- Specific storage
  - depends on flow porosity, fluid compressibility and rock mass (fracture) compressibility
- Fluid potential
  - requires elevation, fluid pressure and fluid density data

Physical Solute Transport Parameters

- Groundwater Velocity and Flow Porosity
  - two types of velocity; Darcy (flux) and interstitial
  - Darcy velocity from flow factors
  - interstitial velocity from tracer experiments and flow porosity; most important and most difficult parameter
  - to quantify in fractured plutonic rocks
- Dispersion
  - the distribution of interstitial velocities in a flow-through system
  - difficult to measure at regional scale where it is dominated by structural framework
- Diffusion
  - in conjunction with an immobile second porosity (i.e., in the rock matrix) represents an effective retardation mechanism for radionuclide transport
  - depends on pore structure of rock, free water diffusion coefficients for ions

study of any natural system, the theoretical methods and conceptual approaches are simplifications, required for analytical tractability, of a complex and heterogeneous system. The degree to which a particular method or approach describes behavior in a natural system, is a function of the scale of investigation, the complexity of the natural system and the severity of the simplifying assumptions. For this reason, it is appropriate to briefly describe the general hydrogeologic characteristics and process of groundwater flow and solute transport in fractured plutonic rocks. Following this description, the importance of scale in obtaining hydrogeologic measurements and applying various theoretical methods is discussed. The basic equations governing groundwater flow and solute transport in geologic media are also discussed.

2.1.1 Groundwater Flow and Solute Transport in Fractured Plutonic Rocks

A plutonic rock mass has structural discontinuities such as fissures, joints, faults, etc. which exist as a result of the imposition of tectonic forces and stresses. These structural discontinuities, or fractures, exist from the microscopic scale (microfissures and cracks along grain and crystal boundaries) through the macroscopic scale (systematic joint sets) to the megascopic scale (regional faults and shear zones observed in aerial photographs). A general and important property of fractured plutonic rocks is that at most practical scales of observation or investigation, structural discontinuities will likely exist at scales which are both smaller and larger than the scale of observation. For example, in assessing the near-field hydrogeologic conditions of an underground opening or repository, fractures will persist at the 1-100 m scale, and will be

the important groundwater flow pathways. The rock blocks defined by these fractures will also be pervaded by smaller scale fissures which may contribute to a secondary porosity. Similarly, the fracture domain defined at the 1-100 m scale will likely be hydraulically bounded by larger scale fractures such as faults or shear zones.

Fluid flow in any geologic medium requires an interconnected, pore space (Figure 2.1). In porous media, this pore space results from intergranular spaces or voids. In plutonic rocks, fluid flow occurs primarily through fractures. This fluid flow can occur at the different scales of fracturing identified above. However, for most practical problems, it is convenient to identify joints or fractures that occur above the microscopic scale as the dominant fluid pathways. This flow path distinction is justified primarily on the basis of permeability magnitudes. Plutonic rocks pervaded by microfractures have permeability values which are usually several orders of magnitude less than the permeability resulting from macroscopic and larger scale fractures. The main fluid pathways in fractured plutonic rock are conceptually illustrated in Figure 2.2.

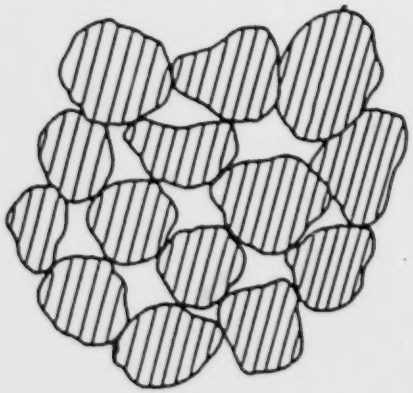
A fundamental understanding of fluid flow and solute transport in fractured plutonic rock is typically based on studies of these processes in both single fractures and multiple fracture systems.

Studies of fluid flow in individual fractures have been undertaken in both the laboratory and the field. These studies have shown that fracture permeability results from the interconnection of a complex distribution of voids or openings created by load-carrying asperities that bridge the fracture open. The distribution of openings within a fracture plane can result in tortuous flow pathways and the

Permeability

Relative Ease of Water Movement

- Requires Interconnected, Fluid-filled Pore Space



Intergranular Pores

Fracture Pores

Figure 2.1 Illustration of the Nature of the Pore Spaces Contributing to Permeability in Porous and Fractured Media

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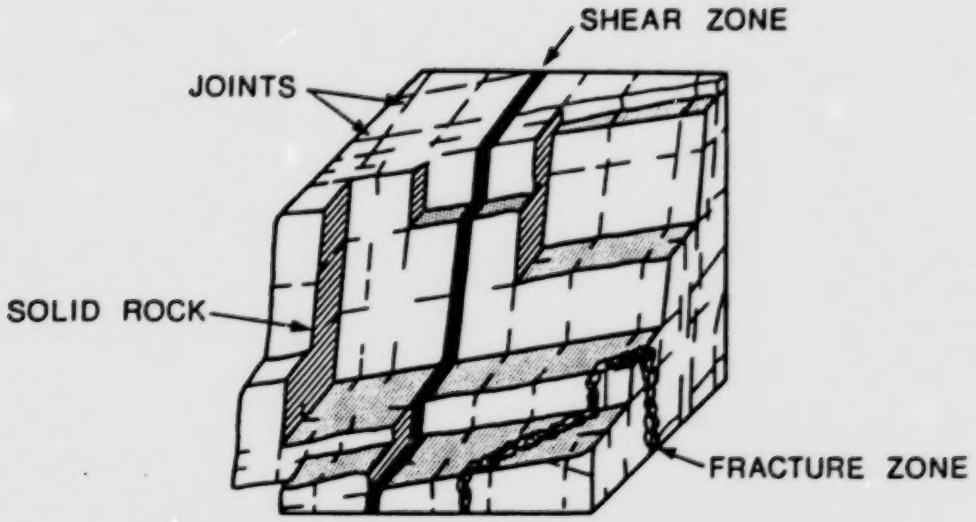


Figure 2.2 Conceptual Model of the Main Flow Paths in Fractured Rocks (from Gale, 1982)

development of independent flow channels. The exact character of flow in single fractures is highly dependent on the roughness of the fracture surfaces.

Laboratory and field studies have also shown that fractures are deformable and that fracture permeability can change in response to changing normal stress (Gale, 1975; Iwai, 1976; Witherspoon et al., 1979) and shear stress (Maini, 1971; Voegele et al., 1981; Makurat, 1985). The permeability change is highly nonlinear, being greatest at low ambient stresses. Experimental studies have also shown that fracture permeability can change in response to changes in temperature (Nelson, 1975; Voegele et al., 1981; Hardin et al., 1982).

Most of the experimental work on single fractures has focussed on the measurement of permeability or flow rate. While flow rate (i.e., volume per time) is important for estimating fluid fluxes to an underground opening or leach and dissolution rates of disposed waste, fluid velocity (length per time) is the important parameter for contaminant migration evaluation. Yet fluid velocity within single fractures is poorly understood. Only a few laboratory and field studies have addressed this problem through the use of tracer migration experiments. These studies show a wide range of fluid velocities which are difficult to predict using permeability data and existing theoretical models. The variation of fluid velocities result from the wide range of fracture openings within a single fracture generated by the complex roughness of the fracture surfaces.

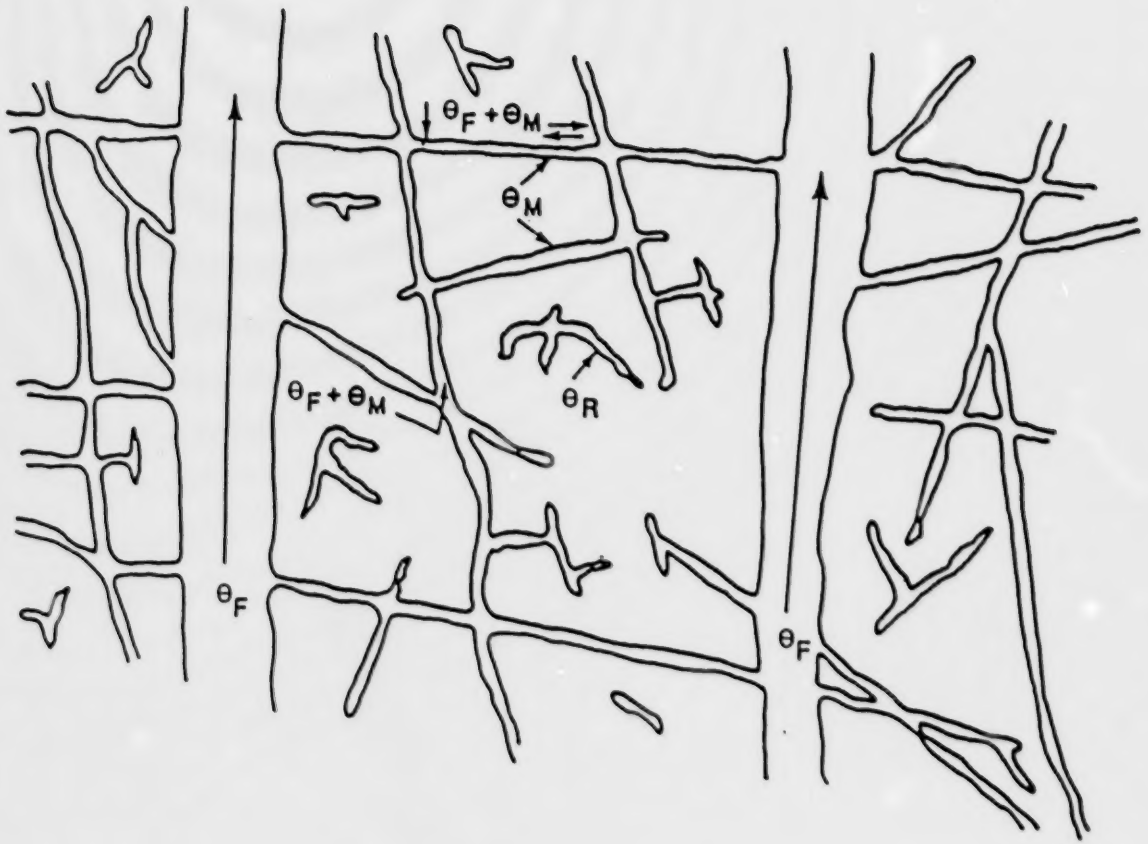
Fluid and solute flowing through macroscopic fractures is now known to interact with the smaller scale microscopic fractures and pores which exist in the so-called "intact rock blocks" separating the fractures. Such behavior is typically described in terms of porosity types. The different types of porosity in fractured crystalline rock

have been discussed by Norton and Knapp (1977) and are schematically illustrated in Figure 2.3. The flow porosity, θ_f, is the effective porosity defined by the macroscopic fractures through which fluid and solute move. The matrix porosity, θ_m, is the interconnected porosity of the rock matrix between the flow porosity fractures, and results from small cracks along grain boundaries and in individual crystals. The matrix porosity is the porosity available for diffusion of solute from the flow porosity.

The interaction between the flow porosity and matrix porosity is important to the assessment of the long term isolation of radioactive waste. Because the pore space of matrix blocks is typically much larger than the flow porosity of the fractures, the rock matrix can act as a significant storage reservoir for fluid and solute. Of greatest importance to the disposal of nuclear waste is the movement of radionuclides from the fluid flowing in fractures to the relatively immobile fluid of the rock matrix. For systems at hydraulic equilibrium, this transfer results from diffusive fluxes generated by concentration gradients between the fracture and the matrix. The importance of matrix-diffusive effects on solute transport in fractured media is schematically illustrated in Figure 2.4.

Field observations of multiple fracture systems in outcrops, recovered core, and underground excavations show that natural fractures:

- are generally planar;
- occur three-dimensionally and often systematically;
- have varying degrees of openness (i.e., many are closed);
- have finite length;
- have rough fracture surfaces; and
- may have secondary fracture infilling materials.



θ_F FLOW POROSITY

θ_M DIFFUSION POROSITY

θ_R RESIDUAL POROSITY

Figure 2.3 Types of Porosity in Fractured Media (after Norton and Knapp, 1977)

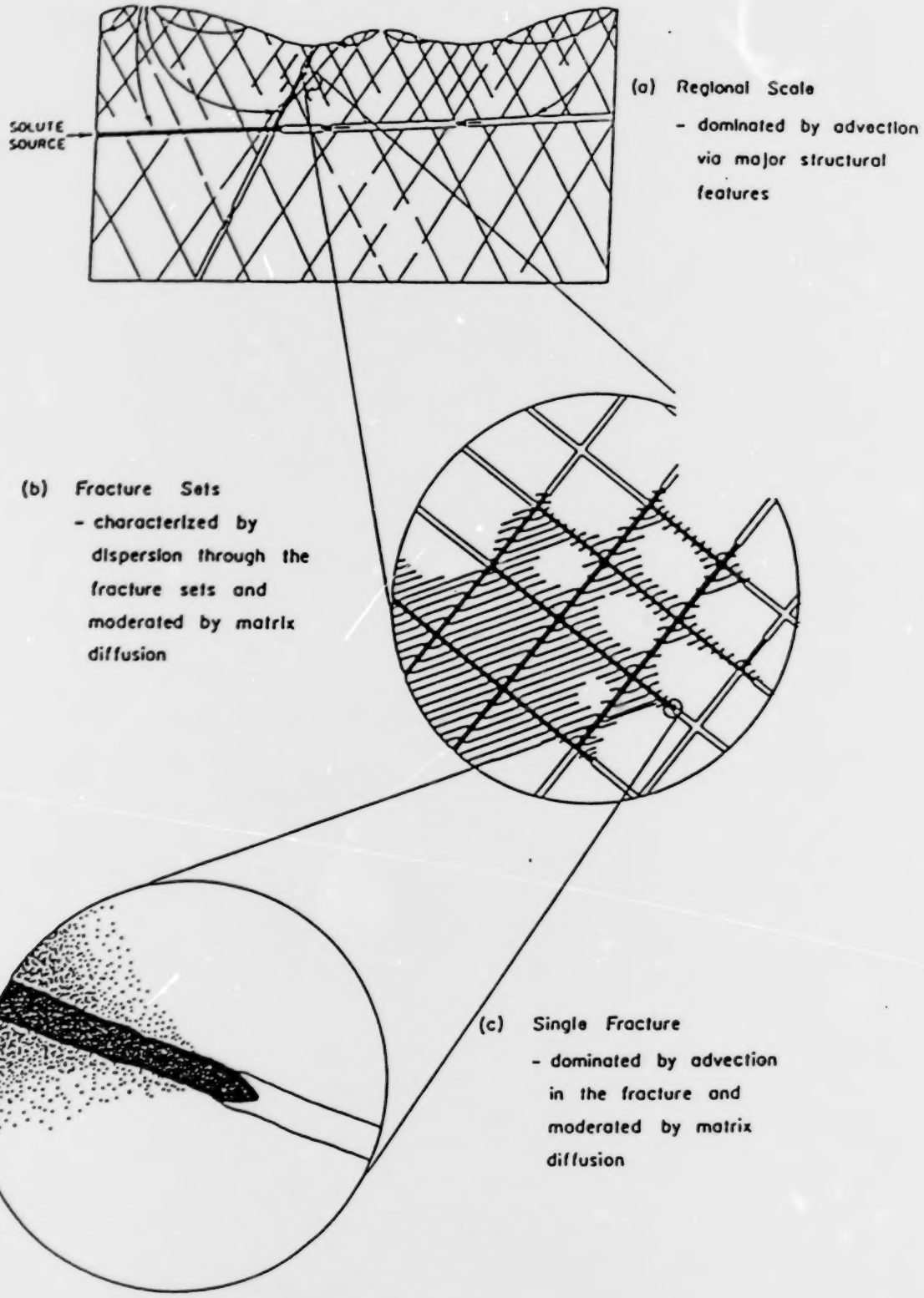

SOLUTE SOURCE
(a) Regional Scale
- dominated by advection via major structural features
(b) Fracture Sets
- characterized by dispersion through the fracture sets and moderated by matrix diffusion
(c) Single Fracture
- dominated by advection in the fracture and moderated by matrix diffusion

Figure 2.4 Solute Transport Mechanisms in Fractured Media (from GTC, 1985)

The bulk permeability of a plutonic rock mass results from the often complex manner in which individual discontinuous fractures form hydraulically interconnected networks. If the fracturing is sparse relative to the scale of the problem under investigation, it is likely that knowledge of the geometric and hydraulic properties of individual fractures and fracture sets would be required to understand fluid flow and solute transport in the medium. In highly fractured media, such an approach may not be feasible and alternate approaches (e.g., equivalent porous media) may be sufficient.

Fluid flow through a network of interconnected but individually discontinuous fractures is primarily governed by the following fracture parameters:

- hydraulic properties or opening of individual fractures;
- fracture orientation;
- fracture spacing;
- fracture length.

From field observations and testing it is known that these parameters are rarely uniform and that they are usually statistically distributed. For example, fracture opening, orientation, spacing and length have been described by log-normal, normal, negative exponential and log-normal distributions, respectively. Furthermore, it has been suggested in a limited number of studies (Miller, 1979; Neuman et al., 1985; Rouleau and Gale, 1985), that individual fracture parameters are spatially correlated (i.e., they are not randomly distributed in space but are correlated with the properties of adjacent fractures). Some of this research has also suggested that fracture properties themselves are cross-correlated (i.e., fracture opening is correlated to fracture length, meaning that longer fractures have larger openings).

The fluid-velocity field, in a fractured plutonic rock, is difficult to determine and may likely be widely distributed reflecting the distribution of fracture parameters that control fluid flow. The distribution of fluid velocities in a geologic medium determines the residence time distribution of conservative solute and their concentration history at discharge locations. The variation of fluid velocity in a geologic medium, about some mean value, is frequently characterized as a dispersion process. The net effect of dispersion in porous or fractured media is to modify the solute arrival or breakthrough curve at a point as shown in Figure 2.5. Dispersion and mixing of solute in a fractured plutonic rock can result from fluid velocity variations at the following scales:

- microscopic scale velocity variations between fracture surfaces and normal to flow, generally assumed to be parabolic;

- microscopic scale velocity distribution within the plane of a single fracture in the direction of flow as a result of fluid flow over and around fracture roughness.

- macroscopic scale variations of mean velocity between individual fractures;

- the variation of mean fluid velocity between macroscopic scale and megascopic scale fractures.

In addition to these hydrodynamic processes, the velocity of the solute can be affected by physical interactions (e.g., diffusion) between the flowing or mobile fluid of fractures and relatively stagnant or immobile pore fluids. The immobile fluids may exist within the fracture and within the rock matrix.

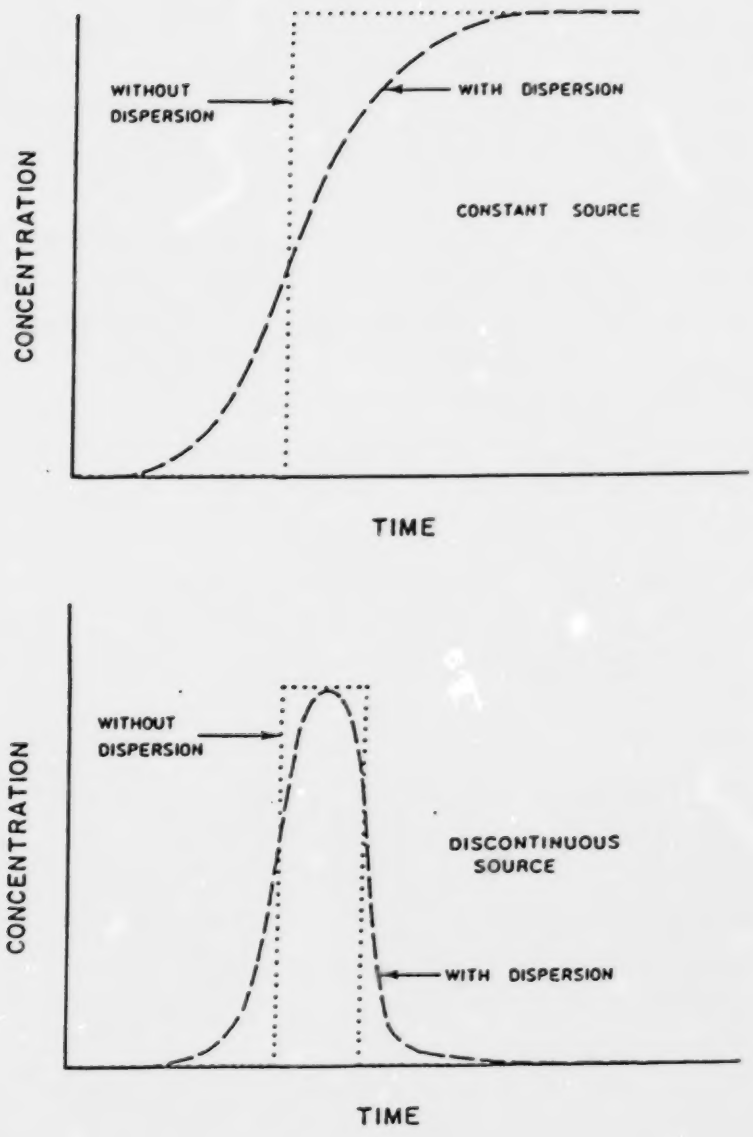


Figure 2.5 Solute Breakthrough Curves at a Sampling Point With and Without Dispersion (from GTC, 1985)

It is generally recognized that performance assessment of a nuclear waste repository requires characterization of potential groundwater flow pathways which may exist at both near-field (repository) and far-field (regional) scales (see Section 2.1.3). The existence of megascopic scale faults and fracture zones with permeability different from that of the bulk macroscopic permeability of the rock mass introduces significant complexities to the groundwater flow system. It is likely that local, intermediate and regional groundwater flow systems, such as those defined by Toth (1963), and illustrated for a homogeneous and isotropic geological system in Figure 2.6, will develop in a much more complicated and structurally controlled manner in fractured plutonic rocks. Major or megascopic scale fractures may act as important conduits channelling fluid between surface and depth or alternatively, because of low permeability, they may act as flow barriers. Groundwater flow systems similar to those shown in Figure 2.7 will likely develop in fractured plutonic rock.

2.1.1 General Governing Equations

Theoretical or conceptual approaches for evaluating hydrogeologic conditions are generally based on usage of governing partial differential equations derived from simple physical laws and material balance considerations. Description of the basic differential equations allows identification of most of the important hydrogeologic parameters that must be evaluated in the performance assessment of a radioactive waste repository.

The basic equation describing groundwater flow in a saturated medium is derived from a material balance equation which can be expressed as:

Advection (In-Out) + Sources - Sinks = Accumulation

Mathematically this is expressed as:

$$\nabla \cdot \underline{u}\rho - Q = -\frac{\partial}{\partial t}(\theta\rho) \qquad (2.1)$$

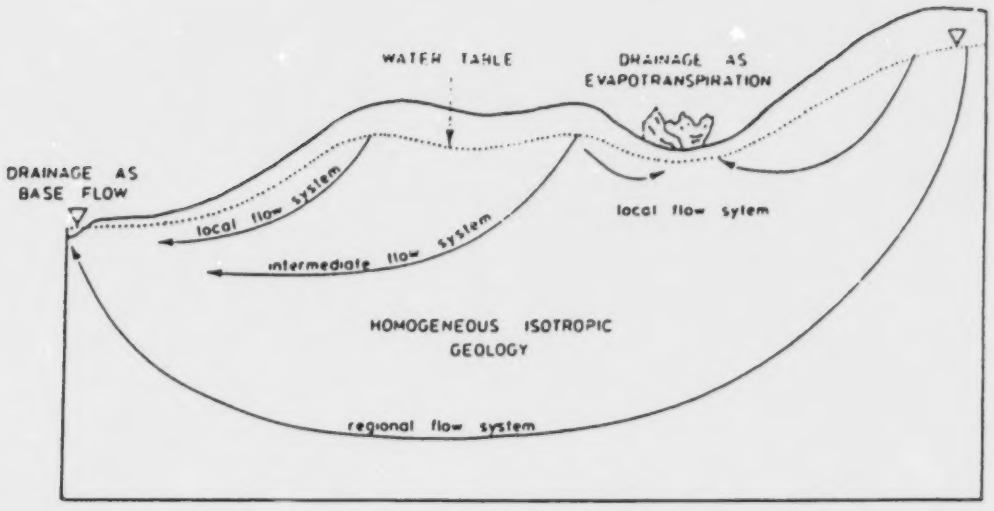


Figure 2.6 Groundwater Flow Systems in a Homogeneous Isotropic Geologic System

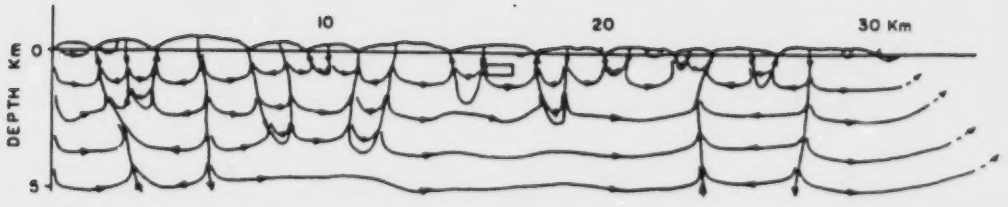


Figure 2.7 Groundwater Flow Systems in a Fractured Crystalline Rock (from Gale, 1982 after Stokes, 1977)

where

Q = mass rate of withdrawal (sink term) per unit medium volume ($ML^{-3}\ T^{-1}$) (a source term is expressed as a negative sink term)

t = time (T)

$\underline{u}$ = Darcy velocity vector (LT^{-1})

θ = porosity (dimensionless)

ρ = fluid density (ML^{-3})

∇ = del operator

The simple physical law relating Darcy velocity to fluid pressure is obtained from a generalized form of Darcy's Law:

$$\underline{u} = -\frac{\rho \underline{\underline{k}}}{\mu} (\nabla p - \rho g \nabla Z) \qquad (2.2)$$

g = gravitational acceleration (LT^{-2})

$\underline{\underline{k}}$ = intrinsic permeability tensor (L^2)

p = fluid pressure ($ML^{-1}\ T^{-2}$)

Z = elevation above reference datum (L)

μ = dynamic fluid viscosity ($ML^{-1}\ T^{-1}$)

Equation 2.2 is presented in terms of pressure, rather than hydraulic head, because the pressure component of the hydraulic head is dependent on fluid properties.

The accumulation term of equation 2.1 is usually expressed in hydrogeologic terms using the compressibility of the medium C_R and the compressibility of the fluid C_w:

$$\frac{\partial}{\partial t} (\theta \rho) = \rho (C_R + \theta C_w) \frac{\partial p}{\partial t} \qquad (2.3)$$

where compressibility is defined as the change in volume per unit volume per unit pressure change.

Combining equations 2.1, 2.2 and 2.3 gives the governing equation for groundwater flow:

$$\nabla \cdot \frac{\rho \underline{\underline{k}}}{\mu} \cdot (\nabla p - \rho g \nabla Z) - Q = \rho(C_R + \theta C_w) \frac{\partial p}{\partial t} \qquad (2.4)$$

The intrinsic permeability tensor in the three-dimensional form of Darcy's Law is a second order tensor with nine components. It is however common practice to reduce these to three diagonal elements by assuming that the principal directions are coincident with the Cartesian axes, x, y and z.

In fractured media, intrinsic permeability is often in a one-dimensional form based on a smooth walled parallel plate analogy to Darcy's Law:

$$k = \frac{(2b)^2}{12} \qquad (2.5)$$

where 2b is the smooth parallel plate opening.

Equation 2.4 can be solved using analytical techniques for simple homogeneous systems and numerical methods for more complex problems. Both analytical and numerical methods require initial conditions and boundary conditions. The necessary initial conditions are a set of initial prescribed pressures. The boundary conditions can either be Dirichlet (a prescribed pressure boundary) or Neuman (a prescribed flux boundary).

The basic equation describing the transport of a dissolved constituent is the advection-dispersion equation. This equation is derived from a material balance of the dissolved constituent

considering retardation, dispersion and decay, and is of the following form:

Advection (In-Out) + Dispersion (In-Out) + Sources - Sinks - Decay = Accumulation

Mathematically this is:

$$-\nabla \cdot (\rho C \underline{u}) + \nabla \cdot (\rho \underline{\underline{D}}) \cdot \nabla C - QC - \lambda \rho \theta RC = \frac{\partial}{\partial t} (\rho \theta RC) \qquad (2.6)$$

where C = concentration of the constituent in solution (dimensionless)

$\underline{\underline{D}}$ = hydrodynamic solute dispersion tensor (L^2T^{-1})

λ = first order decay constant (T^{-1})

R = equilibrium retardation factor (dimensionless)

The advective term of equation 2.6 is expressed in terms of interstitial or pore fluid velocity by dividing by the effective or flow porosity of the medium.

The dispersion term represents spreading and mixing caused in part by molecular diffusion and variations in fluid velocity. The form of the dispersion term assumes that the spreading and mixing may be described by a diffusional process or Ficks laws of diffusion. In an isotropic medium, the hydrodynamic dispersion tensor is a second order tensor, consisting of nine components. In a simple one-dimensional flow field, the hydrodynamic dispersion tensor may be reduced to two components, a longitudinal term, D_L in the direction of flow and a transverse term D_T perpendicular to flow. These terms consist of a mechanical mixing component and a molecular diffusion component.

$$D = \alpha_L |\underline{V}| + D_m \qquad (2.7a)$$

$$D = \alpha_T |\underline{V}| + D_m \qquad (2.7b)$$

where α_L and α_T are longitudinal and transverse dispersivities (L), D_m is the diffusion coefficient of the solute in the medium (L^2T^{-1}) and $\underline{V}$ is the average solute (or interstitial) velocity.

Solution of equation 2.6 also requires initial conditions and boundary conditions. The initial conditions are a prescribed initial concentration. The boundary conditions may be Dirichlet (prescribed concentration), Neuman (prescribed concentration flux) or Cauchy (mixed boundary).

2.1.3 Scales of Investigation

In natural, heterogeneous geological systems, it is impractical, if not impossible, to individually define all heterogeneities which contribute to the overall system behavior. These heterogeneities exist from the microscopic to megascopic scales. At some point, averaged estimates or measures of material properties are required in order to utilize simple physical laws (e.g., Darcy's Law) to describe hydrogeologic processes. The scale at which the representative material properties may be measured and the physical laws hold, is a subject of considerable and current controversy. This scale is often identified as the "Representative Elementary Volume" (REV). Gillham and Cherry (1982) define the REV for hydrogeologic properties as the lower limit of the macroscopic scale (see Figure 2.8). The macroscopic scale is a term used to describe the region where the hydrogeologic property is independent of volume. There is usually an inherent assumption that monitoring instruments or field measurements are sampling, for either physical or chemical properties, a REV. Figure 2.8 illustrates the concept of a REV with respect to the sampling scale for a specific hydrogeologic parameter.

Physical hydrogeologic properties, such as porosity, and chemical properties, such as an ionic concentration, will vary in magnitude at very small scales (perhaps from pore to pore). However, a sufficiently large sampled volume of the system should provide adequate averaging to render the measurement representative. The size of the sample required to assure representativeness may be different for different media. As shown in Figure 2.9, a well or piezometer that may

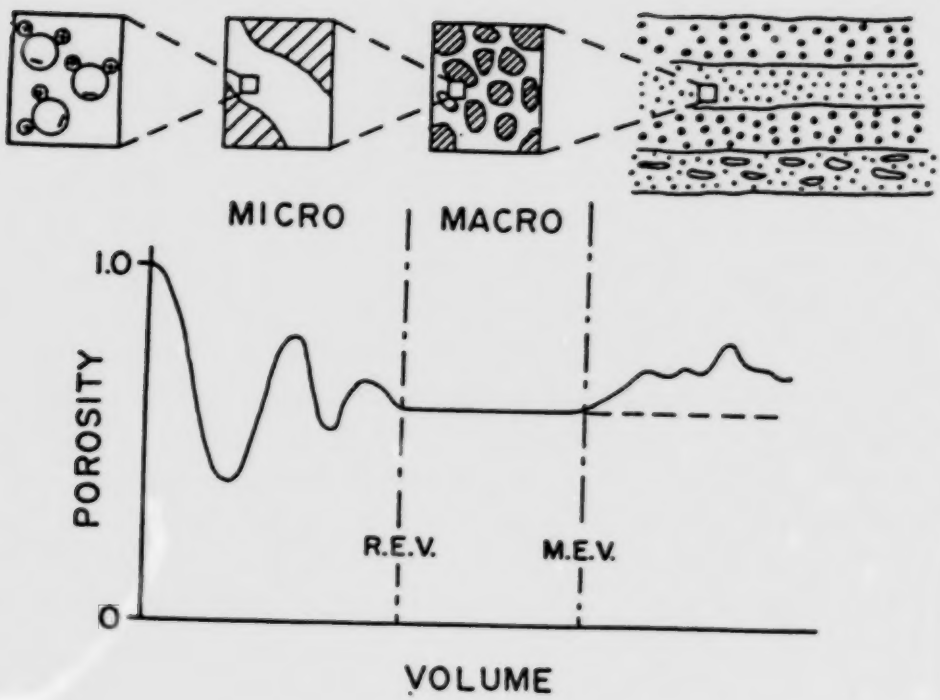


Figure 2.8 Variation of System Properties (porosity) with Sample Size (from Gillham and Cherry, 1982)

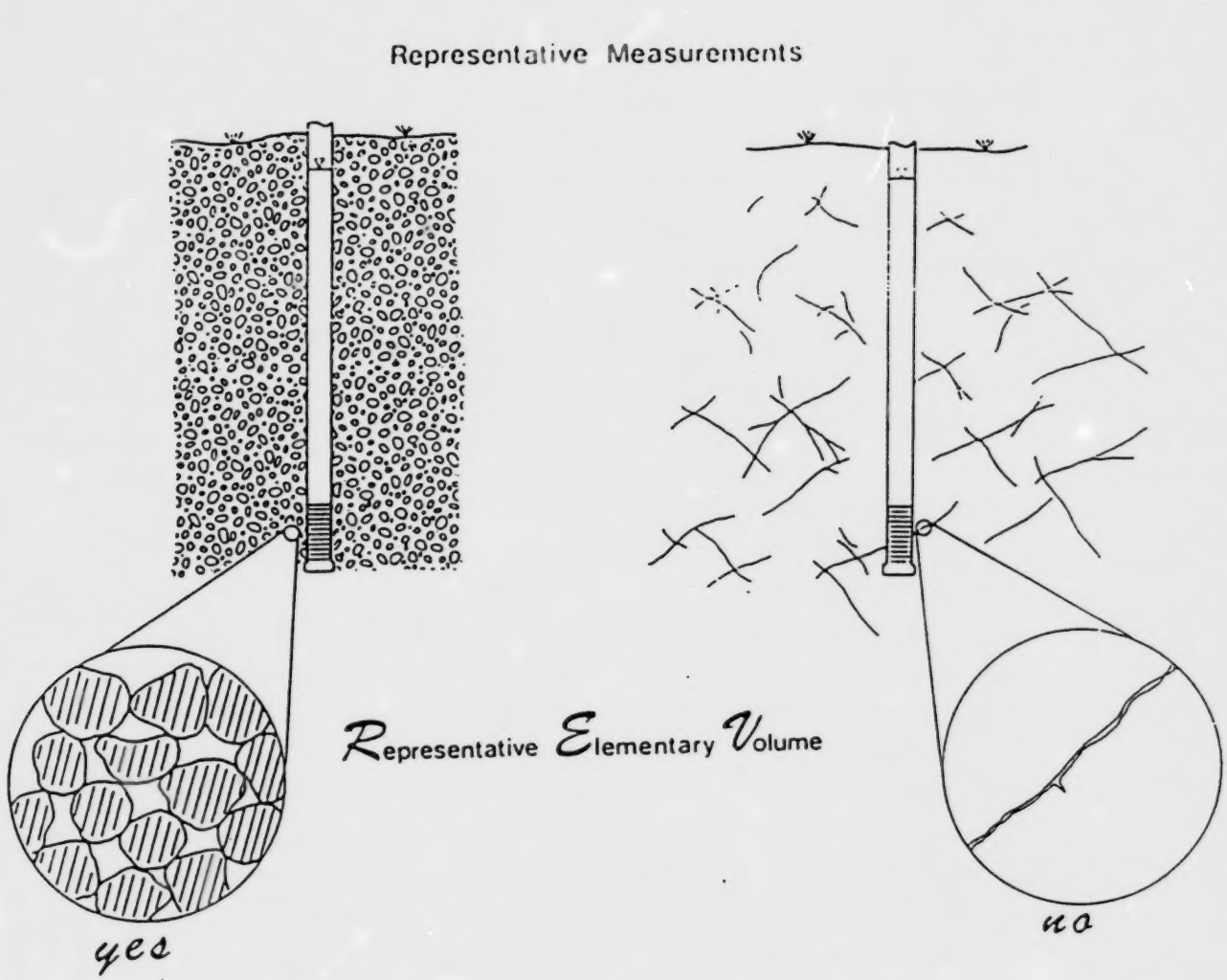


Figure 2.9 Representative Elementary Volume (REV) in the Context of Porous and Fractured Media

be suitable in porous media might be unacceptable in fractured media. Of additional current research interest is the question of whether the individual REV's for flow, solute transport and geochemical mechanisms are of sufficiently similar size to allow transference of data from one to another. For instance, can the velocity derived from the groundwater flow equation be used in the solute transport equation.

Recent theoretical works by Long et al. (1982), Long and Witherspoon (1985) and Hsieh et al. (1985) have addressed the questions of the scale and conditions under which theoretical fracture networks exhibit a REV and behave as equivalent porous media with respect to flow. The works of Long et al. (1982) and Long and Witherspoon (1985), although only theoretical, suggest that continuum behavior is favoured by the geometric fracture parameters of high fracture density and nonuniform fracture orientation, whereas nonuniform fracture aperture distributions detract from equivalent porous media behavior. They further indicate that the size of a REV for flow may have to be large compared to fracture lengths in order to provide a good statistical sample of the fracture population, and that the REV used in regional groundwater flow problems must be small compared to the size of the flow problem such that each REV experiences a constant gradient. From these obervations on theoretical fracture networks, it is clear that the geologic and/or structural framework of the medium defines the hydrogeologic system's REV. The work undertaken by Hsieh et al. (1985) involved the development of a cross-borehole testing methodology for the purpose of characterizing fractured media. Hydraulic analysis of field tests lead Hsieh et al. (1985) to conclude that the fractured rock system behaved as an anisotropic porous medium. It should be pointed out that the data to support this conclusion was limited and some uncertainty regarding the suitability of a porous medium approach to represent fractured rock systems may still exist.

A second very important aspect to the concept of REV's is the scale of interest (GTC, 1985). If the scale of interest is that of laboratory diffusion experiments on intact rock cores, the REV is

likely of the order of several cm^3. If the scale of interest is from the Appalachions to the Hudson Bay Lowlands, or from the Rockies to Lake Winnipeg, the REV may be for practical purposes of the order of tens to hundreds of km^3.

Although it is difficult to be absolute about the dimensions of a REV in fractured plutonic rock, it is possible to distinguish between two important scales of interest in evaluating the performance assessment of a nuclear waste repository. These scales of interest are the near-field or repository scale and the far-field or regional flow system scale. In the near-field scale, groundwater flow and solute transport properties of the rock are influenced by the geomechanical and thermal perturbations created by excavation of the facility and the emplacement of waste. Because fluid flow and solute transport in the vicinity of the repository will likely be influenced by discrete fractures, the REV in the near-field may be quite small, possibly at the single fracture scale. Such a small REV may prohibit the use of equivalent continuum methods and necessitate deterministic or stochastic fracture network models to evaluate flow and transport properties. Furthermore, it is generally recognized (Tsang, 1980; 1985; LBL Panel, 1984; GAIN II, 1984) that in the immediate vicinity of the repository, and likely for several hundred metres from the repository, there is a need to consider the interactions between thermal, geomechanical, geochemical and hydraulic effects. These interactions necessitate the use of coupled hydrologic models (see Section 2.1.5.4). For solute transport in low permeability rocks, near-field theoretical methods need to consider the influence of coupled thermomechanical and thermochemical effects. An example of coupled thermomechanical effects is the change in aperture resulting from the generation of thermal and mechanical stresses. An example of one of the important thermochemical effects in the near-field is the precipitation of secondary minerals. For instance, it is expected that silica leached from the rock near a high temperature waste canister will precipitate some distance away at lower temperatures, clogging pore space in the rock. Table 2.2 (Tsang, 1985) identifies the types of coupled processes likely to occur in the near-field of a nuclear waste repository constructed in fractured rock.

Table 2.2 List of Coupled Processes (from Tsang, 1985)

Thermochemical (TC)
- Thermal Diffusion
- Phase Changes--Equation of State of Solids
- Solid Solution
- Metastable Phases

Thermohydrological (TH)
- Convection Currents (1 or 2 phases) including Buoyancy Flow
- Phase Changes and Interference
- Thermophysical Property Changes
- Thermal Osmosis
- Gas Diffusion:
  - Binary
  - Knudsen
  - Thermal
  - Coupled
- Capillary-Adsorption

Thermomechanical (TM)
- Induced Cracking
- Fracture Deformation
- Thermal Spalling
- Thermal Creep
- Thermal Expansion

Hydrochemical (HC)
- Speciation
- Complexation
- Solution
- Deposition
- Sorption/Desorption
- Redox Reactions
- Hydrolysis
- Acid-Base Reactions
- Diffusion
- Chemical Osmosis and Ultrafiltration
- Isotopic Exchange
- Coprecipitation

Hydromechanical (HM)
- Hydraulic Fracturing
- Pore Pressure Change
- Hydraulic Erosion of Fractures
- Sedimentation of Particles
- Shear Effect Causing Abrasion
- Variation of Fracture Apertures
- Filtration of Particles
- Ultrafiltration

Table 2.2 List of Coupled Processes (from Tsang, 1985) (Cont'd)

VI. Mechanical-Chemical (MC)

These processes will be modified by hydrological and thermal effects, so they are included in processes VII and VIII below.

VII. Thermohydrochemical (THC)

Solution/Precipitation

Time-Dependent Solution and Precipitation

Fluid Transport by Osmotic Effect

Chemical Transport in Gas Phase

Partition between Gas and Solid

Particle Transport (Colloids)

Equation of State

Thermal Diffusion (Soret Effect)

Thermal Osmosis

VIII. Thermomechanical-Chemical (THC)

Phase Change in Mineral Phases

Dehydration

Creep

Hydration and Swelling

IX. Thermohydromechanical (THM)

Hydraulic Fracturing

Triggering of Latent Seismicity

Stress Redistribution

Pore Pressure

Opening and Closing of Joints

Stress Redistribution

Thermal Coupling

Pore Pressure

Spalling

Change of Strength

Stress Corrosion

Hydrolitic Weakening

Hydration

X. Hydromechanical-Chemical (HMC)

These processes were eliminated from consideration because without thermal effects the mass transport is not sufficient to change the geometry except for low temperature precipitation, stress corrosion, and ion exchange producing swelling (e.g. Na for Ca in smectites) at approximately 50°C or below.

XI. Thermohydromechanical-Chemical (THMC)

Piping--Selected Dissolution and Tunnel Corrosion,

Inhomogeneous Leaching

Precipitation

In Fractures

In Matrix

Hydrothermal Alteration of Rock

Heat Pipe Effect with Dissolution/Precipitation

Vertical Vapor-Liquid Cycling Near Canisters

Pressure Solution

The regional or far-field scale of interest can be differentiated from the repository or near-field scale in that thermal and geomechanical effects are generally negligible in the far-field. Only hydrochemical interactions such as sorption, dissolution and precipitation, etc. need be considered for solute transport in the far-field. At the regional scale, it is expected that continuum models in either deterministic or stochastic form will provide the only feasible method of evaluating hydrogeologic conditions. This implies that REVs for the important hydrogeologic processes will exist and that they can be identified at the appropriate scales within the regional geologic and structural framework. Even at the regional scale, there may be a need to consider large scale heterogeneities through individual characterization in deterministic models or by using such known data in conditioned stochastic models (see Section 2.1.6).

2.1.4 Deterministic and Stochastic Approaches

Theoretical methods for studying hydrogeologic conditions fall into two general categories, deterministic and stochastic. Ganoulis and Morel-Seytoux (1985) provide a comprehensive overview of stochastic methods as applied to the study of aquifer systems and much of this discussion on the differences between the two methods is from their excellent review.

The deterministic approach for studying a physical problem is likely the first and more traditional tool in engineering sciences. The deterministic approach is based on the premise that there is a unique relation between the deterministic response $Y_{i,d}$ of say a rock mass or aquifer and its excitation x_j in terms of the rock mass or aquifer system parameters a_p. This means that a law or relation can be found between the above parameters which is of the following functional form:

$$Y_{id} = f(x_j, a_p) \qquad i=1,\ldots n,\ j=1,\ldots m,\ p=1,\ldots k. \qquad (2.8)$$

As shown in Section 2.1.2, this law is usually a result of integration of a governing partial differential equation. The value of $Y_{i,d}$ is the model deterministic response. The true value of Y_i can be written in the form:

$$Y_i = Y_{i,d} + \epsilon_{i,d} \qquad 1 = 1,\ldots n \tag{2.9}$$

where $\epsilon_{i,d}$ is the total error, having assumed a deterministic model, due to several causes such as: i) the intrinsic uncertainties of the aquifer system, ii) the measurement errors of instrument precision and human action, iii) the numerical errors when the governing equations are solved and iv) the structural model error. In using the deterministic approach to evaluate system parameters, a_p, from measured responses or to predict actual system response, Y_i, it is usually implictly assumed that the total error, $\epsilon_{i,d}$, is negligible and that $Y_i \approx Y_{id}$. The current state of the art with respect to studies of flow and solute transport in fractured plutonic rock, is such that the total error, $\epsilon_{i,d}$, is usually not negligible and in fact may be quite large.

The stochastic approach considers the physical parameters of the aquifers, a_p, and the inputs, x_j, as random or correlated variables having probability disribution functions. By using physical conservation laws (e.g., deterministic partial differential equations) or empirical statistical analysis of the available data, the objective of the stochastic approach is to determine the probability distribution of the dependent variable Y_i in the form:

$$P[Y_i \leq y_i] = \zeta(x_j, a_p, y_i) \qquad i=1,\ldots n,\ j=1,\ldots m,\ p=1,\ldots k \tag{2.10}$$

where ζ is an arbitary function of x_j, a_p and y_i.

The stochastic value, $Y_{i,s}$, can be expressed as the sum between the mean (expected) value $Y_{i,s}$ (according to the probability law) and the stochastic deviation or error $\epsilon_{i,s}$, in the form:

$$Y_{i,s} = \left(Y_{i,s}\right) + \epsilon_{i,s} \qquad i=1,\ldots n \tag{2.11}$$

Usually, because of the nonlinear interactions between the aquifer parameters, a_p, and the response, Y_i, there is no equality between the deterministic model value and the stochastic model expected value. By comparing the relations 2.9 and 2.11 and setting $Y_i = Y_{i,s}$, one obtains

$$\epsilon_{i,d} = \left(Y_{i,s}\right) - Y_{i,d} + \epsilon_{i,s} \tag{2.12}$$

Excluding any numerical or experimental or model structural errors, the deviations $\epsilon_{i,d}$ and $\epsilon_{i,s}$ are due only to physical uncertainties of the aquifer system. In this case, the stochastic approach furnishes a formal procedure for evaluating $\epsilon_{i,s}$ or some measure of it such as the standard deviation. This then, is the principle theoretical advantage of the stochastic approach over a deterministic analysis; formal evaluation of error due to uncertainties in the aquifer system. However, application of the stochastic method requires: 1) evaluation of the total deterministic error, which can only be determined from calibration using detailed in situ measurements and 2) verification of the assumed probability distribution functions for aquifer parameters which also requires detailed and comprehensive field measurements.

Use of stochastic methods in groundwater hydrology also requires limiting assumptions for simplifying the mathematical analysis. The two most common simplifying assumptions (Neuman, 1982) are those of stationarity and ergodicity. Strict stationarity implies

that the probability distribution function associated with a particular hydrogeologic parameter, such as permeability or porosity, remains constant in space over the region to which the parameter applies. For example, in a deterministic analyses a homogeneous system will be one in which a particular hydrogeologic parameter (e.g., porosity) is constant. Stationarity imposes the additional constraint that all probability properties associated with porosity must be constant over the system. That is, not only must the best estimate (i.e., mean value) be constant over the system but also the variance, skew, error distribution, etc. must be constant from point to point within the system. Ergodicity means that the probability distribution function can be derived from repeated sampling of an ensemble of statistically equivalent media at a given point in space, or from samples collected at different points within a single medium. The ergodicity assumption allows the analysis of the statistical characteristics of a random variable in one point by knowing the distribution of these properties in the aquifer space. The degree to which the hydrogeologic parameters of fractured plutonic rock obey these simplifying assumptions is generally not known. Because fractures control the fluid flow and solute transport properties of plutonic rock, evaluation of the severity of these assumptions must be made based on the statistical properties and distribution of fractures.

Because of uncertainty of input parameters and system adherence to stationarity and ergodicity assumptions, stochastic methods are currently seeing limited practical use in large-scale hydrogeologic problems. However, considerable effort and progress is being made in the development and application of stochastic methods in particular to radioactive waste disposal problems and a comprehensive stochastic description of hydrogeologic systems may develop in the near future.

In this report both deterministic and stochastic theoretical methods for evaluating the groundwater flow and solute transport conditions in fractured plutonic rocks are discussed. Because

deterministic methods have greater current application and most stochastic methods require a deterministic model to determine output response for samples of input conditions, the deterministic methods are discussed in greater detail.

2.1.5 Deterministic Methods

Deterministic methods for evaluating the groundwater flow and solute transport properties of fractured plutonic rock discussed in this report are broadly categorized as follows:

- Equivalent Porous Media Methods;
- Dual Porosity Methods;
- Discrete Fracture Methods;
- Coupled Process Methods.

2.1.5.1 Equivalent Porous Media Methods. The equivalent porous media concept attempts to represent the hydrodynamics and solute transport processes of fractured plutonic rock using a fictitious continuum. The equivalent porous media method is the simplest of the deterministic methods and, in the context of radioactive waste disposal, has been proposed as a means of evaluating both steady-state and transient groundwater flow systems and multi-dimensional solute transport. Because of its simplicity, the equivalent porous media method is often used as a first approximation of hydrogeologic conditions in lieu of more detailed information.

Governing Equations

The partial differential equation governing fluid flow through an anisotropic continuum is equation 2.4. The appropriate equation governing solute transport in a continuum is the advection dispersion equation given by equation 2.6.

Data Requirements

Use of equations 2.4 and 2.6 to evaluate or predict fluid flow and solute transport in porous or fractured media requires certain reliable data and simplyifying assumptions. Essentially the use of both equations 2.4 and 2.6 requires solution of well-posed initial value - boundary value problems. Such solutions require information on the distribution and value of material properties and the location and type of initial and boundary conditions. With this information, the governing equations can be solved for simple geometries and conditions using analytical methods and, for more complex problems, using approximating numerical methods such as finite difference and finite element methods. Because two governing equations exist, it is appropriate to consider the data requirements for evaluating groundwater flow and solute transport separately.

Consideration of the governing equation describing steady fluid flow, shows that data on the following material and fluid properties are required:

- $\underline{k}$ - intrinsic permeability tensor;
- p - fluid pressure;
- ρ - fluid density;
- μ - dynamic fluid viscosity.

In transient flow, the specific storage parameter, S_s, which is defined here as the amount of water released per unit volume of medium per unit decline in fluid pressure is also required. As indicated in equation 2.3, S_s is often expressed in terms of fluid and medium compressibility as:

$$S_s = \rho(C_R + \theta C_w) \qquad (2.13)$$

where C_R = medium compressibility (LT^2M^{-1})

C_w = fluid compressibility (LT^2M^{-1})

θ = porosity.

In fractured plutonic rocks, the flow porosity is often small. As a result, the specific storage term may be dominated by changes in fracture aperture at relatively early times. That is, the rock compressibility results primarily from closure/opening of fractures as opposed to deformation of the stiffer intact rock matrix. At later times or larger distances, the matrix or unfractured rock compressibility may become the dominant component of the storage term.

In addition to data on material properties, quantification of initial and boundary conditions are essential for evaluating hydrogeologic flow and ambient rock stress conditions. The number of initial and boundary conditions required for solution of the governing differential equations is determined from the order of the spatial and temporal derivatives. For example, for a one-dimensional form of the transient flow equation two spatial or boundary conditions and one temporal or initial condition must be specified.

The equation governing nonreactive solute transport in porous media, requires the follow material properties or parameters:

- $\underline{u}$ - Darcy velocity vector;
- θ - effective or flow porosity;
- $\underline{\underline{D}}$ - hydrodynamic solute dispersion tensor.

Appropriate solute initial and boundary conditions are also required.

Applications and Limitations

The continuum or equivalent porous medium method has application in evaluating the flow properties of fractured plutonic rocks provided certain scale requirements are observed. Work by Long et al. (1982) and Long and Witherspoon (1985) have suggested that, at certain scales of observation and fracture density, theoretical

fracture networks behave as equivalent anisotropic porous media with respect to steady fluid flow rate. Field experiments performed by Hsieh (1985) also indicated that naturally fractured systems may behave as anisotropic continuums with respect to transient flow on the scale of 10's of meters.

The above observations (i.e, regarding anisotropic behavior), together with the difficulty of knowing individual macroscopic fracture characteristics at large or regional scales, promote equivalent porous media methods (as opposed to discrete fracture approaches discussed subsequently), as currently the only feasible method of investigating regional flow systems for repository performance assessment. It is likely that even at the regional scale, major structural features will require individual hydraulic characterization. The principal difficulties or limitations of this application stem from the inability to reliably know the spatial distribution of the material and fluid properties and the location and nature of flow boundaries. This lack of information introduces uncertainty into the conceptualization of a hydrogeologic system and is one of the important limitations of all deterministic methods. It is important that, in performance assessments of a nuclear waste repository, the uncertainty in hydrogeologic conceptualization and material and fluid properties be incorporated in the risk assessment.

Continuum approximations are also useful in the analysis of borehole hydraulic tests to estimate the permeability properties of the rock mass. Permeabilities calculated from borehole tests are generally appropriate for predicting fluid fluxes through a fractured rock mass (on a scale equivalent to the tested rock volume) because the tests are usually based on measured or calculated fluid fluxes. However, it is important to note that interpretation of the measured fluxes and pressure response of a borehole hydraulic test to calculate a continiuum permeability requires knowledge of the fluid properties and the nature of the flow boundaries.

Continuum analyses for estimation of fluid flow rate also have application in determining the inflow rates to an underground waste repository and future leach and dissolution rates of the waste form to the groundwater flow system. Recent theoretical work by Wilson et al. (1983) and Gale et al. (1982) in the Stripa granite, Sweden have shown that groundwater inflow to an underground opening can be reliably evaluated using the continuum approach.

While equivalent porous media methods have demonstrated application in quantifying groundwater flow rates in fractured rocks, the applicability of the method to solute transport studies remains to be demonstrated. Most theoretical work on relatively uniform and simple fracture systems (Schwartz et al., 1983; Smith and Schwartz, 1984; Endo et al., 1984) have shown that solute transport through the fracture networks cannot be adequately described using the governing advection-dispersion equation (see equation 2.6). The principal shortcomings result from a non-uniform and directionally dependent flow porosity and a significant skewness in the breakthrough curves that cannot be described using a simple coefficient of hydrodynamic dispersion.

On a more fundamental level, solute transport through single fractures at both the laboratory scale (Neretnieks et al., 1982) and field scale (Raven and Novakowski, 1986), has been shown to be poorly described by the advection-dispersion equation as a result of flow channelling and solute interaction with immobile fluid in the fracture plane and in the intact rock matrix.

Perhaps the most important and difficult solute transport parameter to determine in fractured plutonic rock is the interstitial pore water velocity. This parameter can be theoretically calculated from the Darcy velocity or flux by using an estimate of effective or flow porosity. However, the complex and hetereogeneous nature by which individual water-filled voids connect in both single fractures and in fracture networks brings into question the validity of estimating fluid

velocity from the Darcy velocity by using a simple effective porosity. Alternatively the fluid velocity can be determined from field tracer tests. However, we know of no large scale field tracer experiment in fractured rock where the solute transport properties have been successfully evaluated using a simple equivalent porous media approach. Furthermore, the few "successful" tracer experiments performed in fractured rock have been performed under induced hydraulic gradients and it is not clear that the solute transport parameters determined from such tests are representative of natural gradient transport properties.

2.1.5.2 Dual Porosity Methods. Dual porosity methods consider the interactions between flowing (fracture) porosity and immobile (matrix) porosity during both groundwater flow and solute transport. The interaction between the dual porosities is of greatest importance in solute transport calculations where the porous rock matrix acts as a sink for solute migrating in the fracture network.

Governing Equations

Simplified equations for groundwater flow in dual porosity media are obtained by associating, with each point in the medium, a small volume that includes a significant number of fractures so that a meaningful average of pressures in the fractures as well as in the pores of the matrix may be defined. Therefore, two average pressures are associated with each point and two equations are obtained for both average pressures in the fractures and in a porous matrix. The first equation is a slight modification of equation 2.4 describing equivalent porous media flow. The two equations are

$$\nabla \cdot \frac{\rho \underline{\underline{k}}}{\mu} \cdot (\nabla p_f - \rho g \nabla Z) - Q = \frac{\partial}{\partial t} (\theta_f \rho) + \frac{\partial}{\partial t} (\theta_m \rho) \qquad (2.14)$$

and

$$\frac{\partial}{\partial t} (\theta_m \rho) = -\omega (p_m - p_f) \qquad (2.15)$$

where ω = a fracture matrix hydraulic conductance parameter; and
f,m = subscripts refer to fracture and porous matrix, respectively.

The parameter ω is related to permeability of the porous matrix, k_m, and the geometry of the matrix blocks, ω', as follows:

$$\omega = \omega' k_m \tag{2.16}$$

The geometry factor ω' is related to the characteristic length, L, of the matrix blocks. For n sets of normal fractures limiting the rock matrix, the geometry factor is:

$$\omega' = 4n(n+2)/L^2 \tag{2.17}$$

Description of the flow of fluid in a fractured porous media requires simultaneous solution of equations 2.14 and 2.15.

The basic governing equation of nonreactive solute transport in a dual porosity media is the general transport equation (2.6) with one modification:

$$-\nabla \cdot (\rho C \underline{u}_f) + \nabla \cdot (\rho \underline{\underline{D}}) \cdot \nabla C - QC - \lambda \rho \theta C - \rho N_v = \frac{\partial}{\partial t} (\rho \theta_f C) \tag{2.18}$$

where:

N_v = the rate of nuclide diffusion from the fractures into the matrix per unit volume.

The subscript f refers to fractures.

Diffusion from the fractures into the matrix is expressed as follows by assuming a spherical geometry of the matrix:

$$\frac{D_m}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial C}{\partial r}\right) = \frac{\partial (C\theta_m)}{\partial t} \tag{2.19}$$

where D_m is the diffusion coefficient for the porous medium matrix and θ_m is the diffusional porosity of the matrix. Equations (2.18) and (2.19) are coupled through equality of solute concentration at the fracture - matrix interface. The rate of nuclide diffusion across this interface, expressed per unit spherical volume, is:

$$N_v = \frac{-3D_m}{r} \frac{\partial C}{\partial r} \qquad (2.20)$$

Data Requirements

Data required to use the dual porosity approach for evaluating fluid flow are generally similar to data requirements for the single porosity (equivalent porous media) method, with the exception that rock properties must be specified for both fractures and the porous matrix. The accumulation term for the porous matrix requires evaluation of a fracture matrix conductance parameter which theoretically can be evaluated from knowledge of the geometry and permeability properties of the matrix blocks.

Data requirements for the dual porosity transport method are also similar to those for the equivalent porous media transport method with some additions. These overall data requirements are:

- Darcy velocity in the fracture;
- fracture porosity;
- matrix porosity;
- hydrodynamic dispersion properties of the fracture;
- matrix diffusion coefficient;
- fracture spacing or matrix block geometry;
- appropriate initial and boundary conditions.

Applications and Limitations

The concept of a dual porosity medium is an idealization of fractured media. The dual porosity concept is an attempt to describe fractured media in terms of average properties. It is more realistic than a simple equivalent porosity approach, but it is still a simplified approximation. The utility of a dual porosity approach in applications has not been demonstrated to any great extent.

Dual porosity flow models may have potential application in the analysis of transient flow conditions where the large fluid storage capacity of the matrix will influence the pressure distribution of the fractures. Such applications include transient well test analysis and transient flow to the repository during construction and operation and later during flooding. The dual porosity method is expected to have minor application in long term regional flow system analysis where steady flow conditions may be assumed to exist.

Dual porosity transport methods have potential application in describing solute transport in rocks where the advection or bulk flow is dominantly through fractures and retardation is primarily by the porous medium matrix. This condition is expected to dominate at most spatial and temporal scales relevant to radioactive waste disposal in fractured plutonic rocks. These spatial scales include both the near field and the far-field.

Application of dual porosity models requires quantification of the matrix rock properties of permeability, porosity and diffusion and the geometrical characteristics of the fractures. Matrix rock properties are usually measured in the laboratory and fracture geometry is inferred from geological observations. The considerable uncertainty in matrix and fracture properties anticipated in fractured plutonic rocks may render the dual porosity method an over-simplification of the natural system and of limited practical use.

Some of this uncertainty can be reduced by obtaining more reliable estimates of matrix rock properties either in situ where natural stress conditions exist or with large fracture - matrix samples in the laboratory subject to representative in situ stress and chemical conditions. Uncertainty in fracture characteristics (hydraulic and geometric) will likely remain a major limitation to the use of the dual porosity methods as a deterministic tool. Use of the dual porosity model in a stochastic framework may prove more useful provided that the appropriate probability distribution functions can be determined for the hydrogeologic parameters.

2.1.5.3 Discrete Fracture Methods. Methods which consider the fluid flow and solute transport properties of individual fractures are termed discrete fracture methods. Discrete fracture methods may be used in conjunction with other deterministic continuum methods or in simple fracture networks. Discrete fracture methods in conjunction with other deterministic continuum methods are the most likely application of the method as a result of the need to individually consider the influence of megascopic scale fractures (such as faults and fracture zones) on local- and regional-scale flow system behavior.

Governing Equations

The equations governing fluid flow and solute transport in discrete fractures are essentially equations 2.4 and 2.6. The only significant modifications may be the representation of permeability through the use of the cubic law (equation 2.5) and appropriate changes in the porosity definition to reflect the fact that the porosity within the fracture is unity.

Data Requirements

Data requirements are essentially those for the equivalent porous media methods with the added requirement of the geometry, hydraulic and solute transport properties of individual fractures.

Application and Limitations

Discrete fracture methods have potential application in characterizing fluid flow and solute transport in the very near-field of a repository (and through repository rooms, drifts and shafts) and in the far field when used in conjunction with other deterministic or stochastic methods. Discrete fracture methods also have potential application to borehole testing when individual geologic structures or fractures can be recognized and isolated.

Examples of applications of discrete fracture methods include characterization of the flow regime in a shallow groundwater flow system (Raven et al., 1985) using the fracture orientation - aperture model of Snow (1965) and modeling of drawdown response to a mined shaft (Guvanasen, 1984). In the former example, the approach was found to provide a good approximation to fluid flow to 30 m depth but overestimated permeability and fluid flow below 30 m depth. In the latter example, the approach was used in conjunction with continuum methods and was shown to be necessary to adequately predict fluid inflow and drawdowns at the site scale. Discrete fracture methods have also been shown to be useful in evaluating the hydraulic and solute transport properties of individual high permeability fractures in otherwise low permeability rock (Novakowski et al., 1985a,b).

A model based soley on discrete fractures provides a theoretically correct flow pattern only if all fractures and connections between fractures are considered. Because of the data requirements for such an undertaking, deterministic fracture network

models have potential application only at small or near-field scales where such data can be reliably obtained. The difficulty of obtaining such data for the far field makes it difficult, if not impossible, to apply the method to regional scale problems.

Even in regional scale problems where the bulk of the media may be represented by some type of continuum, discrete fracture methods for considering the influence of megascopic scale fractures have limitations. In this instance, the limitation derives from the inability to know reliable geometric, hydraulic and solute transport properties of the important large-scale discontinuities for which a continuum approximation is inadequate.

In small scale studies of single fracture behavior, the usually assumed parallel-plate model (Wang et al., 1983) has been shown to be unreliable in its ability to predict fluid velocity from fluid flow rate and permeability data. Actual fluid velocities determined from tracer tests have been shown to be orders of magnitude slower and faster than fluid velocities predicted using the cubic law (Abelin et al., 1983; Novakowski et al., 1985b; Raven and Novakowski, 1986). Therefore, there may be significant difficulty in applying the discrete fracture approach to solute transport evaluations for even the simplest of geometries (i.e., a single fracture). An additional limitation of the discrete fracture method in transport studies is the fact that the solute interactions between the fractures and rock matrix are not considered.

2.1.5.4 Coupled Process Methods. Coupled process methods refer to a series of theoretical methods that attempt to consider the interaction of thermal, mechanical and chemical effects on the groundwater flow and solute transport processes in fractured plutonic rock. For example,

geomechanical, geochemical and thermal effects are expected to influence the near-field hydrogeologic regime as a result of excavation of a repository, and the emplacement of heat-generating radioactive wastes (see Section 2.1.3).

As discussed by Tsang (1985) and listed in Table 2.2, a great number of coupled processes with various degrees of importance are likely to occur during the life of an underground nuclear waste repository. Because most of the coupled processes are only now being recognized, there are few theoretical methods available for evaluating their importance. Most of the methods developed to date are based on continuum approximations. Thermomechanical and thermochemical processes are recognized as two of the more important effects on the hydrogeologic system. Proper evaluation of these effects requires characterization of the thermal, chemical and hydraulic properties of both the intact rock and the fractures as well as the coupling relations between the different processes. This coupling may be one way or two way (feed-back coupling).

It is, however, beyond the scope of this report to identify and evaluate all the important coupled processes that should be addressed in evaluating the performance of a nuclear waste repository. Much work remains to be done, not only in identifying the processes, but in developing appropriate theoretical methods of study for discontinuous fractured media.

2.1.6 Stochastic Methods

Stochastic methods for evaluating the groundwater flow and solute transport properties of fractured plutonic rock discussed in this report are:

- Statistical/Stochastic Data Analysis;
- Sampling Methodologies;
- Finite Order Methods and Analytical Solutions;
- Particle-Motion Methods.

Stochastic methods have potential application in performance assessment of a nuclear waste repository primarily as a result of the inability to attain a complete deterministic description of the spatial distribution of parameters and boundary conditions. Stochastic methods have an advantage over deterministic methods because they attempt to incorporate parameter uncertainties in groundwater flow and solute transport models.

2.1.6.1 Statistical/Stochastic Data Analysis. Statistical/stochastic data analysis are methods that can be applied for a direct analysis and treatment of in situ measurements. These methods (Ganoulis and Morel-Seytoux, 1985) may include time series analysis, Kalman filtering and geostatistical methods such as kriging.

Time series analyses generally have limited applicability to groundwater systems particularily in fractured rocks due to the paucity of hydrogeologic data. The typical application, where data are available, has been to forecast fluid levels (in wells) based on past measurements and on other pertinent data.

Kalman filtering is a statistical method of estimating hydrogeologic parameters (Wilson et al., 1978). Kalman filtering uses matrix equations in the filter. The principal limitation of the method is the dimensionality of the matrices that must be used in groundwater problems. For n parameters to be estimated, one must compute with an n by n matrix. Because of the large number of uncertain parameters

(heads, permeabilities, dispersion coefficients), the method has limited application to regional hydrogeologic problems (McLaughlin, 1978).

Kriging or geostatistics (Matheron, 1967) is a more popular and recently applied method for estimation of hydrogeologic parameters. The geostatistical method, which is also known as the theory of regionalized variables, assumes that the total of geologic processes responsible for hydrogeologic parameters (i.e., fracture development, etc.) can be interpreted as a random (stochastic) process. The variogram function is the basic tool of geostatistics because it describes the spatial correlation between sample values.

The main advantages of the geostatistical method over other stochastic methods is that the uncertainty in input values and output values from the method are reduced because the method is conditioned by known parameter values. In other words, the geostatistical method strives to provide the best unbiased estimate of a material property (e.g., permeability) over a particular subregion based on available measurements in other subregions.

Geostatistical methods have significant potential application in evaluating the hydrogeologic conditions of fractured plutonic rock. In addition to their use in parameter estimation, geostatistical methods have been used with other methods such as conditional Monte Carlo simulation (Jones et al., 1985; Neuman et al., 1985; Winter et al., 1984) in studying flow and transport in fractured crystalline rocks.

The limitations of the geostatistical method are similar to those of most methods based on assumptions of a stochastic process. The system is assumed to be ergodic and, as a minimum, weakly stationary (Neuman, 1982; see Section 2.1.4). The degree to which

hydrogeologic systems in plutonic rock adhere to these assumptions remains to be demonstrated. As a practical consideration, it may not be possible to obtain sufficient data to evaluate the suitability of the geostatistical approach to regional scale problems.

2.1.6.2 Sampling Methodologies. Sampling techniques are probably the most popular and potentially most powerful of the stochastic methods for evaluating hydrogeologic conditions. Sampling techniques can be classified as either a Monte Carlo approach or a stratified sampling approach. In both methods, the effect of heterogeneity of natural media on both fluid flow and solute transport is considered by repetitive generation and solution of random spatial fields. The random spatial fields are usually generated from probability distribution functions of the hydrogeologic parameters controlling flow and transport using various statistical sampling methods. The distinction between Monte Carlo and stratified sampling methodologies lies in their treatment of input variable probability density functions. Monte Carlo techniques basically use a brute force approach while stratified sampling (e.g., latin hypercube) will subdivide the area under the probability distribution function curve in order to minimize the number of samples.

Each random spatial field is solved for flow and transport using a deterministic method. Repeated generation and solution of the random spatial field results in a probability distribution function for the output parameters which typically, for performance assessment of a radioactive waste repository, might include groundwater travel time.

Monte Carlo simulations methods have recently been shown to have considerable application in studies of flow and transport in fractured rocks. Schwartz et al. (1983); Smith and Schwartz (1984); Robinson (1982) and Rouleau and Gale (1986) have used Monte Carlo simulations of discrete fracture networks in the study of fluid flow,

and with particle-motion methods, solute dispersion in fractured media. In these applications the discrete fracture deterministic method is used to solve for the fluid flow and velocity distribution in the fracture network. Monte Carlo simulations have also been used with continuum deterministic solutions of the random spatial fields particularly in the context of performance assessment of a nuclear waste repository (Clifton et al., 1985; Giuffre and Nalbandian, 1981; Petrie and Foley, 1981).

Most sampling methods, whether they are used in discrete fracture or continuum frameworks, have similar data requirements and limitations. In Monte Carlo applications that assume a spatial stochastic process, the probability distribution function (pdf) of the input parameters and the spatial correlation of the input parameters must be defined. For steady flow in discrete fracture networks, this usually requires pdfs of fracture orientation, fracture length, fracture spacing and fracture permeability and some spatial autocorrelation parameter. In a continuum framework, the pdfs and spatial correlation must be specified for material properties such as permeability and porosity. In both frameworks, the boundary and initial conditions may also be described using pdfs. It is essential when using samples to estimate population pdfs to ensure that the samples are representative and not biased by sampling technique or size.

The limitations of Monte Carlo simulation methods are similar to those for most stochastic methods. The major limitations are the assumptions of ergodicity and stationarity required to apply stochastic theory and data availability. It is yet to be shown that the assumptions of ergodicity and stationarity (statistical homogeneity) apply to fractured plutonic rock at the large spatial scales required for regional flow system evaluation. Even if hydrogeologic systems can be shown to have properties characteristic of a stochastic process,

application of the theory requires data on the pdfs of the controlling material properties. These data are generally not available, particularly for the regional scale.

Often the distributions of important material properties required as input are assumed based on various studies. For example, fracture and continuum permeability are generally assumed to be log-normally distributed. Most of these early studies were based on the assumption that the measured values of points in space were statistically independent. However, in reality, these values may show various degrees of spatial correlation and cross correlation. It is not clear how the spatial correlation of, and cross-correlation between, different parameters will affect the previous conclusions about the distribution of various material properties.

Although stochastic methods are the only feasible alternative to deterministic methods in characterizing spatial variability (heterogeneity), much work remains to be done before they "reach the degree of operational simplicity and theoretical reliability required to apply them in hydrologic practice" (Neuman, 1982).

2.1.6.3 Finite Order Methods and Analytical Solutions. These methods are also attempts at incorporating parameter uncertainties in groundwater flow and solute transport models. The aim of these techniques is to predict either the probability distribution or the first few moments (mean, covariance, etc.) of the dependent variable based on input parameter probability distributions. The primary mathematical difficulty in translating parameter uncertainty to output uncertainty lies in the nonlinear nature of output dependence on parameters (Sagar and Clifton, 1985). Therefore, determination of even the lowest moments of the output variable depends on complete probabilistic description of the input parameters.

Various approaches, including first-order methods (Dettinger and Wilson, 1981; Townley and Wilson, 1985), second-order methods (Sagar and Runchal, 1982; Sagar and Clifton, 1985), perturbation methods (Dagan, 1967; Tang and Pinder, 1977) as well as analytical solutions in either the time or frequency domain (Sagar, 1978; Gelhar, 1985; Bakr et al., 1978), have been proposed.

The data requirements and limitation of these methods are the same as those described for Monte Carlo simulations.

2.1.6.4 Particle-Motion Methods. This specialized group of methods is used to evaluate the solute transport properties of heterogeneous media. The essence of the methods is to formulate the spread of solute as a random walk problem. Mass transport is simulated by the directed motion of a large number of reference particles. Particle-motion methods have been proposed to simulate transport in porous media by Ahlstrom et al. (1977) and Schwartz (1977) and in fractured media by Schwartz et al. (1983); Smith and Schwartz (1984) and Schwartz and Smith (1985).

In most of the particle-motion methods, the motion of the particles includes a deterministic and a random component which are related to the mean fluid velocity of the groundwater and dispersion characteristics of the medium. The deterministic component of the particle motion is determined from either deterministic continuum simulation or from analysis of repeated Monte Carlo simulation in discrete fracture networks (Schwartz and Smith, 1985).

The principal data requirements of the method are reliable estimates of the mean fluid velocity. Because these parameters are rarely known over the large spatial scales required for regional flow system analysis, the method has limited application. The method also assumes that the various dispersive mechanisms active in fractured plutonic rock may be represented by a random process. This assumption has yet to be proven.

2.2 GROUNDWATER FLOW PROPERTIES

The groundwater flow properties that should be considered in a site characterization include primary parameters, secondary parameters and boundary conditions. The primary groundwater flow parameters are those that are fundamental to the governing equation describing groundwater movement through geologic media. To this extent, the primary parameters will be a function of the theoretical approach that is adopted to undertake the system assessment. The primary parameters in an equivalent porous medium analysis will differ (if only slightly) from those used in a dual porosity analysis or discrete fracture analysis.

In spite of these potential differences, certain types of information will be common to all the theoretical methods used. These would include information that describes:

- Specified flux/potential values around the periphery of the system under investigation (i.e., boundary conditions);
- Driving force of the hydrogeologic system-typically referred to as the hydraulic gradient or change in fluid potential in space;
- Resistance of formation to fluid flow which may be referred to as the hydraulic conductivity;
- Storage capacity of the hydrogeologic system typically described by a parameter known as the specific storage;

The exact nature of the information required may vary depending on the theoretical approach being adopted. A discrete fracture approach for example, will base its estimate of the formation

resistance on individual fracture properties (e.g., aperture) while an equivalent porous media approach will evaluate a permeability by comparing the response to that of porous media.

Each of these hydrogeologic information requirements is discussed in detail in the following sections with regard to their relative importance in the groundwater flow equation, the scale at which related parameters should be measured (as it pertains to the siting of a nuclear waste repository) and the currently available techniques and equipment that are best suited to the evaluation of these parameters.

2.2.1 Boundary Conditions

In addition to the groundwater flow and solute transport parameters that must be evaluated as part of any repository site assessment, it is essential to accurately define the area over which these parameters need to be evaluated. To a large extent, the perimeter of the area of interest will be determined by the presence of identifiable or definable hydrogeologic conditions such as hydraulic potentials and/or groundwater fluxes. These hydrogeologic conditions are commonly referred to as boundary conditions since, by definition, they are coincident with the periphery of the region of interest.

Boundary conditions should correspond to regions of known groundwater conditions. In actuality however, groundwater conditions are never known precisely and some uncertainty will always exist with regard to the assumed boundary conditions. This uncertainty may be minimized through a variety of tactics. For example, the distance from the repository site to the boundary location will have a direct impact on the propagation of uncertainty associated with boundary values. By selecting boundaries at sufficiently large distances from the repository, this effect can be minimized. Unfortunately, this approach, although minimizing the effect of boundary conditions, necessitates the characterization of a larger region which may

substantially increase the cost of data collection. Alternately, the impact of boundary conditions may be assessed through a sensitivity analysis depending on the theoretical approach being used to perform the analysis.

Theoretically, flow boundary conditions may be classified as specified flux or potential. These values may be either constant or time varying. Suitable locations at which boundary conditions may be evaluated typically coincide with either a geographic or geologic feature. These features include groundwater divides associated with recharge or discharge zones. Zero flux boundaries can be assumed to exist along planes of symmetry or at the edge of a low permeability region. Such an assumption is typically applied to the lowermost boundary of a hydrogeologic system.

The upper most boundary is subject to a variable (both spatially and temporally) flux known as groundwater recharge. It is difficult to precisely estimate the quantity of precipitation that eventually reaches the water table and recharges a groundwater system. Various approaches have been tried to evaluate this quantity, the most common employing water budgets or lysimeters. Water budget techniques typically try to estimate infiltration by quantifying the component processes of the hydrologic cycle. These processes include precipitation, surface runoff, evaporation, transpiration and infiltration. Theoretically, by evaluating all of the other components, infiltration should be calculated as the difference. Unfortunately such an approach is based on the presumption that the individual components may be determined at least as accurately the parameter to be estimated. While this may be true in the case of precipitation and possibly even surface runoff, it is definitely not the case for the evaporation and transpiration components of the budget. These components may each comprise signifi.nt portions of the water budget (e.g., 25 - 50%) and are difficult to quantify with any degree of accuracy. As a result, infiltration is subject to significant sources of error.

Another possible method of quanitifying infiltration is through the use of a lysimeter or infiltration collection device. Such techniques are more commonly employed in unconsolidated media than in fractured rock systems. Even in these applications however effects arising from construction methods (e.g., surface depressions, modified vegetation, higher hydraulic conductivity due to disturbed soil) may bias the collected data.

2.2.2 Hydraulic Conductivity

The formation resistance to fluid flow (or conversely its ability to transmit flow) is quite often expressed in terms of a parameter known as the hydraulic conductivity. The hydraulic conductivity combines several of the parameters that appear in the groundwater flow equations including fluid and formation properties. For a porous media model, hydraulic conductivity (K) is typically expressed as:

$$K = \frac{k\rho g}{\mu} \qquad (2.21)$$

where: k = intrinsic permeability (L^2)
ρ = fluid density (ML^{-3})
g = gravitational acceleration (LT^{-2})
μ = dynamic fluid viscosity ($ML^{-1}T^{-1}$)

Hydraulic conductivities are essential for the proper hydraulic characterization of a groundwater flow regime. This characterization is required to provide information required in the evaluation of such quantities as:

- pathlines of radionuclides released from a repository;
- travel times along these pathlines;
- flux rates through the repository (to determine corrosion rates of canisters and leach and dissolution rates).

Groundwater fluxes are needed both at the near-field and the far-field scales. At the near-field scale, fluxes are used for the characterization of radionuclide release rates to the groundwater system. For example, the flux of groundwater entering the repository would be used to establish corrosion rates of waste canisters along with leach and dissolution rates of the radionuclide waste inventories.

Groundwater fluxes are required at the far-field scale for a variety of purposes. The nature of the groundwater flow between the proposed repository site and regional discharge points will serve to delineate the extent of the region that should be encompassed by a regional assessment. This definition can be obtained by examining the pathlines of water particles that originate at the repository. Pathlines can be defined by constructing models of the groundwater regime (ranging from simplified flow nets to numerical models) based on available piezometric and permeability information. In addition to defining the region of interest, pathlines form a necessary ingredient in the calculation of travel times to the accessible environment (i.e., to discharge points). These times are required to estimate the reduction in radionuclide loading resulting from radioactive decay. Groundwater fluxes at the far-field scale are also required to evaluate the dilution of the released radionuclide between the repository and eventual discharge point.

As identified above, hydraulic conductivity should be evaluated at both a near-field and far-field scale. The near-field scale is typically of the order of 10's to 100's m while the far-field scale is of the order of kilometres. The far-field region is generally regarded as the region in which processes such as heat transport and groundwater flow may be decoupled.

Evaluations being conducted in fractured rock systems must deal with the anisotropic and heterogeneous nature of these systems. In a homogeneous and isotropic system, the hydraulic conductivity along

the travel path between the repository and the discharge point could be characterized by a single measurement. Unfortunately, geologic systems are rarely homogeneous and isotropic with respect to their hydrologic properties. It is therefore necessary to either evaluate an average hydraulic conductivity along the travel path of interest or perform the characterization and the subsequent analyses incorporating the heterogeneity that exists along the travel path. The scale of the required hydraulic conductivity measurements will depend on factors that determine the length of the pathlines most likely to be followed by released radionuclides, such as the proximity of discharge zones to the repository. Hydraulic conductivity measurements at the desired scale may be limited by constraints imposed by available testing techniques (e.g., how large a volume of rock can be tested over a reasonable length of time). To this extent, the scale of both required and feasible hydraulic conductivity measurements for site characterization will be somewhat site dependent.

The scale of the required hydraulic conductivity measurements will also depend upon the theoretical method proposed for the analyses. A finite element or finite difference porous media equivalent model of the groundwater system will require average hydraulic conductivity values for each grid block/element which may easily be on the order of 10's to 100's of metres. For such a model, a detailed spatial definition of hydraulic conductivity over the region of interest is also required.

Secondary Factors

While hydraulic conductivity is the parameter which has been designated as being primary, it must be remembered that it is composed of a number of other parameters representing both fluid and rock properties such as fluid viscosity, density and permeability.

There exist a number of processes that can alter the hydraulic conductivity of a geologic medium. These include processes that involve change in:

- temperature - which may affect fluid viscosity and density, the stress state (hence permeability) of the medium due to thermal expansion, and the permeability due to thermal cracking and precipitation/dissolution of geochemical constituents;

- stress - which may affect the permeability of the medium;

- concentration - which may affect fluid properties such as density and viscosity and, under severe circumstances, may alter permeability.

Measurement Techniques

Hydraulic conductivity of geologic media may be evaluated by a number of techniques depending upon the theoretical approach being adopted for the analysis and the scale of the required measurement. A general classification of hydraulic conductivity evaluation methods might include:

- Discrete Fracture Approach - based on either equivalent single fractures or measurement of fracture characteristics in conjunction with the cubic law;

- Equivalent Porous Media - analyses of traditional permeability test methods using porous media theory.

The discrete fracture approach to the evaluation of hydraulic conductivity does possess several advantages. Fracture characteristics which are required for such approaches are capable of being measured

and lend themselves much more readily to a probabilistic treatment of the hydrogeologic regime. Adequate technology is available to directly measure parameters such as orientation and spacing (e.g., from cores, televiewer and TV logs). Unfortunately current technology is inadequate to properly characterize natural fracture apertures many of which are likely on the order of 1 to 100 um. From a quantitative point of view, apertures of the order of 100 um are most likely very significant hydraulically, while those of the order of 1 um are likely insignificant. However, the range of 1 to 100 um is the common range for most naturally occurring fractures. This inability to accurately characterize fracture openings prohibits the use of the discrete fracture approach for hydraulic conductivity estimates.

An alternate approach (to the direct measurement of the opening) is to use standard hydraulic tests to calculate the fracture characteristics of an idealized fracture which is theoretically capable of providing the observed response. This approach is probably most applicable to the near-field and while it does offer significant advantages over the method of direct measurement, it is subject to certain assumptions. For example, some assumption regarding the number (or spacing) and distribution of fracture openings of these idealized fractures must be made.

Unfortunately, a major drawback of such an approach is the inability of theory to relate the measured permeability (openings) to fluid velocity values (i.e., the validity of the cubic law). The nature of naturally occurring fractures (rough, uneven walls and containing infillings) probably accounts for the inability of the smooth walled parallel plate theory to replicate observed field behavior.

Equivalent porous media approaches can use any of the classical hydraulic tests employed in unconsolidated media and include both steady and transient tests for laboratory and in situ conditions.

Basically, all hydraulic conductivity tests consist of inducing a perturbation on a hydrogeologic system. By measuring the response of the groundwater regime to the perturbation and comparing the observed response to a theoretically calculated response, the hydraulic conductivity of the medium may be calculated. The perturbation may take the form of a lowering of the hydraulic head (e.g., through a pump test) or the raising of the hydraulic head (e.g., constant head injection tests, most pulse tests, and slug tests). Hydraulic conductivity tests may be generally classified as single borehole, multiple borehole, or large scale and laboratory tests. The most common of these techniques are described below:

Single Borehole Tests

- Slug Tests consist of measuring the temporal variations in head that occurs when an isolated test zone is instantaneously subjected to a change in hydraulic head. The test allows a fairly reliable estimate of the horizontal hydraulic conductivity to be made although specific storage estimates are typically only good to within one order of magnitude. Slug tests are best suited to media of higher permeability (greater than 10^{-8} m/s for test intervals of the order of 10 m).

- Pressure Pulse Tests are conducted by subjecting an isolated test interval to an instantaneous change in pressure and then monitoring the response. Pressure pulse tests are well suited to low permeability environments (to 10^{-13} m/s Raven, 1980; to 10^{-14} m/s Wilson et al., 1979; Grisak et al., 1985). They do however suffer from certain limitations. For example, the tested volume of the rock is generally quite small (on the order of a few wellbore diameters) and, due to introduction of transient pressure pulse, the test is more susceptible to equipment compliance than steady state or long term transient tests.

- Constant Head Injection Tests consist of injecting water to an isolated section of a borehole until a steady flow rate is obtained. These tests are commonly employed for evaluating fractured rock permeability and can be used in situations where the permeability is between 10^{-5} and 10^{-11} m/s (Raven, 1980). One advantage of this technique is its applicability to small diameter boreholes since little downhole instrumentation is required. It should be noted that while downhole pressure measurements are not always necessary or feasible it is desirable to obtain such information whenever possible. This reduces the uncertainty surrounding the exact nature of the perturbation induced on the system and eliminates the need to consider head losses in the drill string, casing or tubing which may be significant for high flows, deep wells or small diameter wellbores. While this item is mentioned as part of constant head injection tests, it is equally applicable to all test methods. If a steady state analysis method is to be used, care must be taken to ensure that such conditions are reached. Doe and Remer (1980) have shown that violation of this assumption (i.e., neglecting medium storage) can lead to an error factor of two to three in permeability estimates. The tests do offer the advantage that, under steady-state conditions, both wellbore storage and equipment compliance effects should be negligible.

- Pump Tests involve inducing a perturbation into a saturated formation by the withdrawal of groundwater (usually at a constant rate) from an isolated portion of the formation. Horizontal permeability estimates may be obtained from either drawdown or recovery portions of the test. Pump tests may be limited by a number of equipment related problems associated with the need to pump water from small wellbores at significant depths (greater than 100 m).

Surface pumps, for example, are subject to depth limitations, while downhole pumps are subject to wellbore restrictions. Air lift pumping (a method of evacuating the wellbore by injection of air) is another commonly employed technique for conducting pump tests. Difficulties associated with this method include the ability to obtain accurate downhole head measurements and complications arising from the injection of a highly compressive second phase. Pump tests have been used extensively in porous media but their application to rock are best suited to more permeable fractured rocks (greater than 10^{-9} $m \cdot s^{-1}$, Earth Technology Corp., 1985). In low permeability media (less than 10^{-9} $m \cdot s^{-1}$), the pump test response can often be masked by wellbore storage effects making analysis of the test data unreliable.

Large Scale Tests

- Borehole Interference Tests involve stressing the formation by the injection or withdrawal of fluid from a single borehole and monitoring the response in other boreholes. Such tests are useful since they provide an estimate of hydraulic conductivity at a scale larger than most single borehole tests (i.e., equal to the borehole spacing) as well as an indication of the spatial variability of this value (i.e., heterogeneity). Interference tests may use any of the single borehole perturbation techniques (e.g., pump tests, injection tests) and as such are subject to the same limitations.

  Although multiple borehole interference tests do test hydraulic conductivity over larger regions, the uncertainty associated with such tests is typically much higher than that of single tests. This is due to a number

of reasons:

- boundary conditions are more complex (e.g., infinite fracture assumptions are likely to be less applicable);

- wellbore storage may impact both pumping and observation wells;

- a larger region is likely to be more affected by heterogeneity.

- Mine Drainage observations have been used at a number of research sites to estimate large scale permeabilities. Most notable of these is Atomic Energy of Canada's (AECL's) underground research laboratory (URL) and the ventilation shaft excavation at Stripa, Sweden. In these experiments, flow rate into some portion of the facility was measured and together with observed pressure head declines within the rock mass, were used to calculate permeability averages. Difficulties associated with these experiments include reliability/accuracy of inflow estimates as well as the impact of seasonal infiltration on shallow monitoring points. Nevertheless, permeability estimates obtained using such approaches are useful in that they assess values over large areas.

- Groundwater Dating Techniques may be used in conjunction with estimated travel paths and hydraulic heads to obtain permeability estimates over large distances. Marine (1981) used this approach to evaluate hydraulic conductivities over a large region in the vicinity of the Savannah River Plant at Aiken South, Carolina. The major difficulty with such an approach lies in the uncertainty associated with the ages of groundwaters, most techniques

being only order of magnitude correct at best. Other uncertainties are associated with the travel paths and the hydraulic gradients that may have existed over the life of the water being dated, i.e., hydrogeologic systems which are not at steady state.

- Lunar Tides are an example of a natural phenomenon that may be used to obtain permeability estimates over a large region. In this application, the imposed perturbation is in the form of strain responding to tidal stress. By knowing the magnitude of the imposed stress together with the compressibility of the formation, the permeability required to yield an observed water level response can be calculated. The major source of uncertainty associated with this approach is the accuracy of the strain calculated over a large scale. Suffice it to say that while such methods show promise they are, as yet, unproven.

Laboratory Tests

- Laboratory Tests are commonly used in the evaluation of hydraulic conductivity and typically take the form of permeameter tests (either constant head or pressure pulse) conducted on intact and fractured core samples. Laboratory tests offer the advantage of a well controlled environment for the performance of the test. However, this advantage is offset by the uncertainty associated with tests conducted under unrepresentative conditions using disturbed samples. In fractured media, this problem is particularly acute since it is extremely difficult to obtain a naturally fractured rock specimen without inducing some effect (e.g., separation). Attempts have also been made to replicate in situ temperature and pressure (stress) conditions in the laboratory. The

success of such attempts remains uncertain. While permeameters have been identified as the most commonly used laboratory test apparatus a variety of other techniques have also been reported in the literature. Borehole tests, for example, can be conducted on ultra-large specimens of core obtained using a ring of small diameter boreholes.

No single test technique can be identified as being best suited for all testing programs. Numerous different techniques can be used (subject to certain restrictions) to obtain reliable permeability estimates. The reliability of permeability measurements can be said to be a function of three factors:

- the equipment;
- the technique used to conduct the test;
- the analytical method.

The test equipment can introduce error associated with equipment compliance, resolution and precision of the measurement components (e.g., pressure transducers) and pressure dissipation due to such things as screen losses and leaky packers. These items should be quantified prior to implementation of any field program under the same conditions which will be encountered in the field.

The technique used to conduct the test is crucial to determining its reliability. The accuracy of pressure readings, for example, depend on the calibration of the pressure transducers to a known set of responses. Care must be exercised to ensure that drift of the transducers does not give erroneous readings. Both the frequency and reliability of flow rate and drawdown measurements affect the accuracy of the test results. The magnitude of the induced

perturbation must be sufficiently large so that equipment resolution is not a problem yet not so large that formation or equipment deformation is significant.

The exact precision, accuracy and detection limits required for pressure measurement devices (e.g., gauges and transducers) and flow meters will depend on a number of factors. Some of these factors depend upon test related aspects such as the magnitude of the induced perturbation. A pulse test corresponding to a pressure rise of 9.8 kPa (1 m of water) will require different accuracy and precision than one using a perturbation of 98 kPa (10 m of water). The test duration will also impact the magnitude of the drawdown in a pump test and this in turn will affect the required resolution for pressure or water level measurements. Other related parameters which will impact the required resolution and detection limits of flow meters are the permeability and length of the test interval.

Probably the largest source of error in test analyses is through the use of analytical techniques that are inappropriate for the test that was conducted. This inappropriateness typically arises through the violation of assumptions that are inherent in the analytical technique. These assumptions permit an analytical solution of the flow equation to be obtained and facilitate the test analysis. The most common of these simplifying assumptions include:

- test zone is horizontal and of infinite areal extent;
- aquifer is homogeneous, isotropic and of uniform thickness;
- density and viscosity changes of the fluid are negligible;
- formation gradients are negligible compared to those induced by the test;
- wellbore storage effects are negligible;
- head loses through the well screen are negligible;
- flow is laminar (e.g., Darcy's Law) holds.

In addition to these general assumptions, a number of other assumptions may be employed depending on the nature of the analytical solution. These may include:

- flow from the well is radial, that is the well is fully penetrating and the test zone is isolated by low permeability units;
- flow rate (head) of the well is constant with time.

Table 2.3 summarizes the most commonly employed hydraulic conductivity evaluation methods, their advantages, disadvantages and conditions for which they are best suited. In general, it can be said that reliable permeability estimates may be obtained from a variety of techniques provided the assumptions inherent in the analytical technique accurately match test conditions. Violation of these assumptions may significantly impair the accuracy of the results. Steps must be taken either in the design of the test or in the subsequent analyses to ensure that assumptions which are employed in the test analyses are valid. If for example, the analytical technqiues assume that flow is horizontal and radial, this test condition can be enforced using a guarded triple packer injection methodology proposed by Louis (1974). Alternately, such a test could be reanalyzed using a technique that would account for its higher dimensional geometry.

2.2.3 Specific Storage

Specific storage is an indicator of the ability of a formation to produce/add water from/to storage. As such, this parameter is of greatest importance in hydrogeologic regimes subject to transient perturbations. The groundwater regime in the vicinity of a nuclear waste repository will be subjected to several stresses that will induce transient perturbations. These stresses would include those that arise from the construction and operational periods of a

Table 2.3 Hydraulic Conductivity Test Methods

Test	Range of Hydraulic Conductivity* (m/s)	Test Volume	Equipment Requirements	Advantages	Limitations
Constant Head Injection	10^{-5} to 10^{-11}	f(test duration, permeability)	- isolated test interval - accurate flow meter - water level/pressure measurement	- widest K range of all techniques - minimal downhole equipment - few depth limitations - easy analysis	- accuracy/precision determined by flow rate measurements - uncertainties may be introduced due to steady state assumption
Pulse Tests	10^{-9} to 10^{-13}	several wellbore diameters	- isolated test interval - piston and pressure transducer	- good in low permability	- equipment compliance and wellbore storage may be significant - small test volume may make skin effects significant
Slug Tests	greater than 10^{-8}	comparable to slug volume	- isolated test interval - water level/pressure measurement devices	- simple to conduct	- most applicable to unconsolidated media or highly fractured crystalline - specific storage estimates may be unreliable
Pump Tests	10^{-4} to 10^{-7}	depends on test duration and permeability	- isolated test interval - pumps and accurate flow rate measurements - head/pressure measurement technique	- may be used to test large volumes	- surface pumps depth limited - downhole pumps constrained by wellbore diameter - air lift method make pressure measurements difficult - most applicable to higher permeability, but nonlaminar flow may occur in vicinity of borehole
Interference Tests	depends on well spacing typically greater than 10^{-8}	depends on well spacing and test duration	- depends on perturbation technique - preferable continuous water level/pressure measurements in isolated sections of observation wells	- provides indication of large scale heterogeneity and fracture interconnectivity	- difficult to analyze quantitatively due to heterogeneities - media must he highly permeable or wells close together - quantitative analysis difficult

*Assuming a test interval on the order of 10 m

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Table 2.3 Hydraulic Conductivity Test Methods (cont'd)

Test	Range of Hydraulic Conductivity (m/s)	Test Volume	Equipment Requirements	Advantages	Limitations
Mine Drainage	- depends on test duration and monitoring location - possibly 10^{-5} to 10^{-11}	- potentially large 10's to 100's m^3 depending on test duration, K	- requires new excavation at depth - monitoring points within radius of influence of test	- tests a large volume	- may require long test times in low permeability media - may be limited by flow rate measurements in low permeability media - costly - may be difficult to analyze
Ground Water Dating	- probably greater than 10^{-10}	- km^3's	- isotope analyses of groundwater	- tests large volume	- subject to assumptions regarding flow paths and gradients - gives average value - groundwater ages unreliable
Lunar Tides	- unknown	10's to 100's m^3	- water level measurements	- inexpensive	- based on ideal fracture model with largely unknown mechanical properties

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waste repository (e.g., the temporary depressurization of the groundwater regime in the vicinity of the facility) as well as those induced after closure (e.g., buoyancy effects due to waste heat generation).

Specific storage is therefore of importance in determining groundwater fluxes in transient systems. The need for groundwater flux evaluation has been discussed in detail in Section 2.2. Briefly, flux evaluation is required to estimate travel times, dilution volumes and assist in the calculation of source terms (based on corrosion rates, leach and dissolution rates).

Specific storage parameters need to be evaluated where transient effects are important. This will be at the near field scale. Specific storage parameters need only be evaluated on a far-field scale if the groundwater system is subjected to a transient perturbation at this scale. One such transient perturbation that may be of interest is the seasonal variation in infiltration and surface water levels. It is unclear however whether such cyclical behavior would be significant over the time scale of interest (e.g., 1000's years). Other transient perturbations that may be of interest may be long term climatic changes that significantly alter the surface water levels in the vicinity of a repository.

Geologic processes (e.g., tectonic movement, earthquakes, glaciation) may also impart some transient behavior onto the regional groundwater system. For the time scales of interest such behavior requires examination.

Secondary Factors

Specific storage is composed of fluid and medium properties, both of which are subject to variation as a function of other variables. Fluid specific properties include density and

compressibility whereas medium properties include porosity and formation compressibility. In a dual porosity approach, these latter parameters need to be evaluated for both the fracture and matrix. Fluid density is affected by a number of processes such as changes in temperature, pressure and dissolved solids concentration. Fluid compressibility may vary as a function of either temperature or pressure.

Similarly formation compressibility is affected by temperature. Tammemagi and Chieslar (1985) reported that the modulus of elasticity of rock samples is irreversibly affected by temperature. The modulus of elasticity of a material is inversely proportional to its compressibility. Porosity is known to be affected by temperature (Page and Heard, 1981) although the exact nature of this relationship is unknown. Given the relatively small variation of porosity as a function of temperature, together with the natural variation in this quantity, the consideration of porosity variation as a function of temperature is probably unwarranted.

Measurement Techniques

Methods that can be used to evaluate the specific storage of a formation may be classified in either of two categories:

- direct measurement from formation hydraulic tests (e.g., pump tests);
- measurement of the constitutive parameters.

The first of these classifications uses the results of a transient aquifer test to evaluate the specific storage directly. Values of specific storage evaluated in this manner are subject to considerable uncertainty with factors such as equipment compliance and wellbore storage typically giving rise to errors.

The second category includes those techniques that evaluate the individual components of specific storage (e.g., fluid and formation compessibilities, porosity and density). The major difficulty associated with such an approach is the extrapolation of parameters measured under one scale to a field situation of a significantly different scale. For example, laboratory analyses based on core samples are often used in this approach. While the extrapolation of laboratory measurements of fluid properties, and even porosity, to the field will probably yield acceptable results, it is unlikely to be the case for porous media equivalent values of formation compressibilities. Heuze et al. (1981) have compared modulus of elasticity values obtained from field measurements to those determined by laboratory testing for crystalline rocks. The results of this comparison indicated that field modulus values are generally significantly less (e.g., 14 to 67%) then those measured on intact cores in the laboratory. These observations may be attributed to a size effect which relates the introduction of more discontinuities with increasing sample size. It is important therefore when evaluating specific storage on a component by component basis to evaluate the components at the scale for which the specific storage evaluation is required.

Large scale formation compressibility estimates may be obtained through a variety of techniques including geophysical borehole techniques and the responses to natural phenomena (e.g., earthquakes). Table 2.4 summarizes the most commonly used methods of evaluating formation compressibilities and their limitations.

It is also important to recognize that the porosity term, which is included in the specific storage equation, is meant to describe that portion of the specific storage arising from the fluid compressibility. As such, the porosity value that should be included in this evaluation is the total porosity (in an equivalent porous media approach), as distinguished from the fracture, effective and residual

Table 2.4 Formation Compressibility Measurement Techniques

Technique	Applicable Range	Test Volume	Equipment Requirements	Advantages	Limitations
Laboratory Compression Tests	No Limit	Cores	- uni or tri-axial loading equipment, strain gauges	- accurate measurements	- measurements may not be representative of larger scale values
Acoustic Logs	Not known	10's m^3 to 100's m^3	- acoustic logging tool consisting of sets of probes and receivers	- in situ conditions	- formation density must be assumed
Borehole Jacks	$<10^{-11}$ Pa^{-1}	100's m^3	- hydraulic jack with gauges	- large area	- reduction of strain data theoretically complicated - equipment compliance may be significant - poor accuracy - biased to radial direction
Dilatometers	$<10^{-10}$ Pa^{-1}	10's m^3	- dilatometer and deformation measurement device	- applicable at depths up to 200 m	- may not be suitable to crystalline rock environments - biased to radial direction
Borehole Extensometers	10^{-10} Pa^{-1}	10 - 100 m^3	- sensitive deformation guages	- in situ vertical compressibility measured	- expensive

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porosities. In fractured crystalline rocks, by far the major component of total porosity is the matrix porosity. Suitable estimates of this value can be made from laboratory measurements on cores, subject to representative stress conditions. Alternately, such estimates may be inferred with less reliability from any one of a number of downhole geophysical logs, such as neutron, gamma, gamma-gamma or resitivity logs. All of the borehole geophysical techniques should be used with caution since the values obtained by these methods are based on certain assumptions or auxiliary data (e.g., regarding fluid or formation properties). Table 2.5 presents the commonly used techniques for the determination of porosity.

2.2.4 Fluid Potential

As evidenced by the groundwater flow equation, groundwater movement occurs in response to a potential energy gradient. In hydrogeologic systems where fluid velocities are low, the potential energy at a specific point may be defined in terms of its elevation potential and pressure potential. Quite frequently this quantity is reported in terms of a hydraulic head (units of length). In constant density systems such an approach is quite acceptable. In variable density environments (due to differences in salinity, temperature, or pressure) such estimates should be normalized to a reference density. This necessitates knowing the density of the in situ fluid as well as the borehole fluid if water levels or pressure measurements, in a standing column of water, constitute the measurement.

The magnitude of fluid flow within a groundwater system (e.g., its flux) is directly proportional to the rate of change of fluid potential in space (i.e., the hydraulic gradient). Again one of the difficulties encountered in the measurement of hydraulic gradients is the problem of scale. This problem applies to both the averaging interval of individual measurements as well as the distance between successive measurements.

Table 2.5 Porosity Measurement Techniques

Technique	Applicable Range	Test Volume	Equipment Requirements	Advantages	Limitations
Immersion	± 0.1%	- core size	- laboratory apparatus e.g., scales, oven calipers	- good for interconnected matrix porosity	- does not typically give values under in situ conditions - accuracy not good for crystalline rock
Mercury Infusion	± 0.01%	- core size	- laboratory apparatus e.g., balance, oven, mercurcy displacement measurement apparatus	- good for interconnected matrix porosity - provides pore size distribution	- not typically measured under in situ conditions
Grain Density	± 0.1%	- core size	- laboratory apparatus e.g., balance, oven, caliper, grinding equipment	- good for total porosity	- not measured under in situ conditions - destructive test method
Electron Scanning Microscope	± .0001%	- thin sections (≈10's um)	- scanning electron microscope	- accuracy	- only extremely small samples can be analyzed
Neutron Logging	± 1%	- limited to area around borehole	- neutron logging tool e.g., probe, dector, recording instrumentation	- measured under in situ conditions - gives total porosity	- subject to interference from alternate forms of hydrogen - variations in borehole size may affect accuracy
Neutron-Neutron	± 2%	- limited to area around borehole	- neutron generator and either gamma ray or thermal energy detector	- measured under in situ conditions - gives total porosity	- accuracy in crystalline rock not adequate
Gamma-Gamma	± 0.1%	- limited to area around borehole	- requires gamma ray source and detector	- measured under in situ conditions - gives total porosity	- inferred from grain denity - require caliper logs

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In this regard, the measurement of representative fluid potential is very similar to hydraulic conductivity. Although fluid potential is a scalar, it is strongly influenced by the presence of heterogeneities and this aspect of the hydrogeological system may dictate the required spatial definition within the regime of interest.

The existence of variable density fluid may impact more than the magnitude of fluid potential. Nelson and Oberlander (1984) have concluded that under some conditions the commonly employed concept of a scalar energy potential may not be appropriate for use in hydrogeologic systems having non-homogeneous fluids.

Secondary Factors

Factors that affect fluid density, such as changes in temperature, pressure or dissolved solids concentrations, may have a significant impact on hydraulic head measurements. In the case of piezometer measurements, the downhole density should be determined and the head should be recalculated to a constant reference density.

Measurement Techniques

Fluid potentials may be obtained by two possible methods. In one method the region of interest is isolated through the use of packers and the formation is allowed to recover to its natural pressure level (i.e., pressurize the isolated interval). A pressure transducer within, or connected to, the interval allows the formation pressure to be recorded. This information, together with the elevation of the isolated region, will enable the total fluid potential to be calculated. A number of precautions must be taken to ensure the measurements are reliable. For example, sufficient time must be allotted to allow the water pressure and temperature within the rock to recover from its exposure to the pressure and temperature of the open borehole (i.e., recover from borehole history effects). Care must also

be taken to ensure that the pressure readings obtained from the transducer are accurate. This may mean pre and post test evaluation of the transducer calibration as well as ensuring that downhole conditions (e.g., temperature, salinity) do not adversely affect the performance of the equipment.

The other commonly employed technique of obtaining a total fluid potential is through the use of a piezometer. Piezometers typically consist of an isolated screened interval with a standpipe to surface. The water level within the standpipe will provide an indication of the average fluid potential of the formation over the screened or packer-isolated interval. Care must be taken in using piezometers in hydrogeological regimes that are characterized by significant variations in formation-fluid density. Such density variations (due to salinity and/or temperature) must be taken into account if the spatial distribution of the fluid potentials is to be meaningful.

Piezometers may be constructed in a number of different configurations such as single, multiple or multiple port piezometers. Whatever the design, it is essential that the measurement interval be isolated from the remainder of the piezometer and wellbore. This may be accomplished by either packers or grout or bentonite seals. The integrity of the seal should be checked after its installation by stressing the isolation interval and monitoring other regions for a response. One drawback that does exist with the use of piezometers is the amount of wellbore storage that may exist. Excessive amounts of wellbore storage will delay the observed response of a piezometer to a hydrogeologic system perturbation. For this reason, it is advisable to construct piezometers of the smallest diameter casing that is feasible.

Water levels within piezometers are typically measured using a water level tape referenced to a known datum, typically the top of the piezometer casing. It is important that the elevation of the top of the casing be determined accurately and verified on a regular basis subsequently.

In deep boreholes it may also be necessary to correct for departures of the borehole from the vertical in calculation of the elevation head of the test interval. This requires that accurate surveys of borehole orientation be completed immediately following the completion of drilling. Uncertainty in borehole plunge of a 1-2 degrees can introduce an uncertainty of several meters in elevation head for deep boreholes (greater than 300 m depth).

In fractured crystalline rocks, the length of the packer isolated interval or the screened interval can also introduce significant uncertainty in the calculation of fluid potentials. This uncertainty results from poor definition of the elevation of the hydraulically important structures that usually control the fluid pressure or water level in a test interval. For example, if a 10 m packer-isolated test interval is used and the locations of the fractures responsible for the observed pressure are uncertain then the calculated fluid potential (which is the sum of the elevation and pressure heads) can only be as accurate as the test interval length. This uncertainty can be reduced by permeability profiling of the test interval to determine the exact location of the controlling hydraulic structures or by the use of short test intervals.

The advantages and disadvantages of fluid potential evaluation techniques are summarized in Table 2.6.

2.3 PHYSICAL SOLUTE TRANSPORT PARAMETERS

A number of distinct yet interrelated processes contribute to the movement of solute through geologic media. Specifically these include:

- advection;
- dispersion;
- diffusion.

Table 2.6 Methods of Evaluating Fluid Potential

Technique	Applicable Range	Equipment Requirements	Advantages	Limitations
Pressure Measurement	0 - 40,000 kPa	- packer isolated zone - pressure gauge or transducer and recording equipment	- fast response time - continuous monitoring - through-the-bit techniques enables measurement during drilling	- density corrections may be required - temperature may impact transducer reading - packer leakage may affect accuracy - deep piezometers may require correction for non-vertical nature
Piezometers	theoretically no limit	- isolated borehole interval - standpipe - water level tape	- most reliable in shallow, fresh water systems - inexpensive	- discrete measurements - density corrections may be required - wellbore storage may delay response - datum should be verified regularly - leaks at standpipe joints and by packers may affect accuracy

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Advection refers to the movement of dissolved solute as part of the groundwater system. The groundwater velocity is therefore the primary parameter controlling the advection process. The Darcy velocity is required to evaluate the flux of a dissolved solute, while the interstitial velocity can be used to evaluate travel times. In most geologic media, the interstitial velocity is calculated as the Darcy velocity divided by flow porosity.

The dispersion process is meant to describe the mixing that occurs due to velocity variations within the hydrogeologic system. Dispersion is typically evaluated in terms of two variables, the average interstitial velocity and the dispersivity.

The final solute transport process that may be significant in low permeability fractured rock is that of molecular diffusion. This process may be significant in portions of the hydrogeologic system that have low hydraulic gradients or high concentration gradients. Molecular diffusion into the rock matrix may create a significant sink for solute. The molecular diffusive process of solute in geologic media may be characterized by an in situ diffusion coefficient that incorporates the tortuosity and porosity of the medium.

2.3.1 Groundwater Velocity and Flow Porosity

Velocity is a term used to describe two quantities in a hydrogeologic system, namely the Darcy velocity and the intersitial velocity. The Darcy velocity of groundwater, within a hydrogeologic system, is the primary parameter describing the advection of solute. The solute flux through a plane of interest may be calculated as the product of the Darcy flux and the solute concentration. An accurate spatial and temporal distribution of the groundwater velocity profile is essential to the determination of radionuclide releases to the environment. Interstitial groundwater velocities are required for the calculation of travel times which are essential to determining the

breakthrough time as well as the solute reduction due to radionuclide decay. Interstitial velocities may be theoretically calculated as the Darcy velocity divided by the effective or flow porosity.

The scales at which groundwater velocity measurements are required are similar to the scales at which permeability and hydraulic potential measurements are required. As with these measurements, either an average groundwater velocity over a given path length (e.g., from a repository to a discharge point) or the variation of velocity along this path length will be required. The scale over which the average velocity is required will be defined by the geometry and hydrogeologic parameters of the system that is being evaluated.

Secondary Factors

Darcy groundwater velocities are dependent upon hydraulic gradients and hydraulic conductivities. In addition to these parameters, the interstitial velocity is also influenced by the flow porosity of the medium. As a result, the processes that affect these parameters also directly affect groundwater velocities. A temperature change within the groundwater system will impact groundwater velocities by a number of mechanisms. A temperature increase will cause the density and viscosity of the formation fluid to decrease while the intrinsic permeability and porosity of the formation may either decrease (due to thermal expansion and associated closure of fractures) or increase due to thermal cracking or accelerated dissolution of the rock matrix or infilling material. Associated with the density decrease of formation fluid is an induced buoyancy effect due to its thermal expansion. This process may be significant in the vicinity of a nuclear waste repository and may result in significant increases in hydraulic gradients over those measured under natural conditions.

Measurement Techniques

Darcy groundwater velocities may be evaluated by a number of techniques. The most common of these is to estimate the quantity as the product of the hydraulic conductivity and hydraulic gradient over a specific flow path (streamline). The major advantage associated with this method is the ability to calculate new velocity estimates if the hydrogeologic system is subjected to a change in hydraulic gradients.

Another method of estimating the groundwater Darcy velocity is through the use of a technique such as borehole dilution. This method involves monitoring the change in concentration that occurs within an isolated interval containing a tracer of known concentrations. There are a number of difficulties associated with such a technique. Care must be taken to ensure that the flow rates are an accurate reflection of natural groundwater gradients and do not reflect borehole history effects. Resolution difficulties may occur in low permeability media and may dictate the use of long test times (e.g., due to small concentration changes). Other difficulties that may arise are associated with geochemical processes (e.g., adsorption, ion exchange) that may cause solute reduction which may be mis-interpreted as removal due to advection.

Interstitial velocities are most reliably measured through the use of multiple borehole tracer tests. An estimate of the flow porosity can also be made from such a test if the Darcy velocity is known. The majority of the tracer tests reported fall into one of three categories:

- Natural Gradient Tests - Offers the advantage of measurements made under unperturbed conditions and gives estimates of natural in situ velocity;

- Radial Tests - Convergent are usually more successful than divergent tests (due to higher tracer capture) but both may be used to estimate flow porosity;

- Injection - Withdrawal or two well tracer tests are commonly employed in fractured media due to the fact that the flow field is strongly developed between the two wells and is least influenced by the often complex and uncertain boundary conditions characteristic of flow in fractures. Again these tests are used to estimate flow porosity.

As with all tests employing tracers, care should be taken to ensure that the tracer used is truly inert (i.e., moves with the fluid).

Groundwater dating techniques can also be used to estimate average regional groundwater velocities based on assumed flow paths. However current age dating techniques cast considerable uncertainty on the reliability of these estimates. The major methods of estimating groundwater velocity parameters are summarized in Table 2.7.

2.3.2 Dispersion

The dispersive transport of solute within a hydrogeologic system may be described as the mechanical mixing that occurs due to variations in fluid velocities within the media.

The dispersion process is generally assumed to be a function of both the mean interstitial velocity and a characteristic parameter known as dispersivity. Dispersivity may be thought of as representing the velocity distribution about the mean value. While, in theory, dispersivity is a second order tensor, it is, for practical reasons, generally only evaluated in terms of a longitudinal and transverse component (see Section 2.1.2). Dispersivity is known to be dependent

Table 2.7 Measurement Techniques for Velocity Related Parameters

Test	Quantity Measured	Tested Distance	Equipment Requirements	Advantages	Limitations
Natural Gradient Tracer Test	Interstitial velocity	m's	- suitable tracer, injection and monitoring capabilities (e.g., boreholes and probes)	- gives in situ nautral velocity	- difficult to predict natural flow directions in fractured rock - tests conducted under natural gradients and therefore need long test times and short test distances
Radial Tracer Test	Flow porosity	m's to 10's m	- as above	- shorter test times and larger test volumes	- gives interstital velocity under perturbed state - solute capture may be limited in radial divergent tests
Injection Withdrawal Tracer Test	Flow porosity	m's to 10's m	- as above	- shorter test times	- solute capture may be limited - need to consider flow field geometry in test analysis
Borehole Dilution	Darcy velocity	borehole diameter	- as above	- gives Darcy velocity under natural conditions	- may require long test times - non-directional
Groundwater Dating Techniques	Insterstitial velocity	100 m's to km	- groundwater age dating techniques (e.g., isotope analyses)	- gives average values over large distances	- current groundwater dating techniques have high uncertainty - also flow paths may be subject to uncertainty
Hydraulic Conductivity and Gradient Estimates	Darcy velocity	10's m	- variable depending on technique to estimate hydraulic conductivity	- can be used to estimate velocities under natural or perturbed conditions	- conductivities and gradients should be measured at same scale - sufficient hydraulic definition may be difficult to obtain

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on the scale of the system over which it is being measured. This poses a potential problem in extrapolating laboratory and field measurements to larger scales.

Secondary Factors

Dispersivity may be regarded as a measure of the distribution of velocities along a set of pathlines that originate from a common area (e.g., within a repository) to a common discharge area (e.g., a lake). As such, any factors that may impact the magnitude of velocities along these lines may be regarded as affecting the dispersivity. This would include physical variations in parameters that describe fracture network geometry that may impact pathlengths and permeabilities.

Measurement Techniques

There are significant difficulties involved with the estimation of dispersivity values. These difficulties are associated with various aspects of dispersivity including:

- basic theoretical concept;
- scale;
- evaluation of component values.

Dispersivity is not an actual field parameter that can be directly measured, but is a parameter which represents the distribution of average velocities along a specific set of streamlines. As a result, the only manner by which it is feasible to evaluate dispersivity (under field conditions) is to fit a value to a known set of observations assuming a specific governing equation holds.

The field tests most commonly used to create the observations required to obtain dispersivity estimates are tracer tests. Tracer tests (Table 2.7) may be conducted in a variety of formats including

two well and natural gradient tests. A major difficulty arises in trying to extrapolate values obtained from such tests to larger scale regional applications. This is due to the fact that dispersivity is scale dependent.

2.3.3 Diffusion

As a solute transport process, diffusion is typically only important in regions having high concentration gradients and/or low interstitial velocities. Under these conditions dispersion does not dominate the total mixing process. In a fractured crystalline rock environment, diffusion into the rock matrix may be a significant sink for solute.

Observations of dissolved solids and gases in porous media show that diffusion occurs at a much slower rate in a porous medium than in free water. These observations may be attributed to the irregular network of pore walls that inhibit the true random behavior of the diffusive process. This effect is typically incorporated into a diffusion coefficient that is calculated specifically for the medium of interest. Several researchers have developed relationships to evaluate this quantity (Bear, 1972; Lerman, 1976) and typically incorporate such physical charcteristics as the porosity and tortuosity and the free water or uninhibited diffusion coefficient. Tortuosity is the ratio of the actual path length in a hydrogeologic system to the shortest distance between the ends of the pathline. Typically, however, the tortuosity is not measured directly and the diffusive process is evaluated in terms of a porous media diffusion coefficient specific to a particular medium.

Secondary Factors

The diffusive process describes the natural spreading that occurs in the presence of a concentration gradient independent of velocity. This spreading is a function of both the internal energy of the molecules and the physical properties of the solvent. The internal energy is directly affected by the temperature of the solution with increasing rates of diffusion occurring at higher temperatures.

Physical properties of the solvent that influence diffusion include the viscosity of the fluid (also influenced by temperature) as well as the concentration of other solutes within the solution. Most of these properties affect the diffusivity through a complicated set of relationships dependent on the nature of the solute(s) and the intermolecular forces associated with them. Typically such relationships are evaluated empirically for a specific case of interest.

Other factors which impact diffusion include additional solute properties (e.g., physical size of solute molecule relative to pore size) and pressure. Pressure is reported to be inversely related to molecular diffusion however the magnitude of this variation is extremely small and can generally be discounted in most applications.

Measurement Techniques

Due to the nature of conditions under which molecular diffusion is most significant (i.e., low intersitial velocities and/or high concentration gradients) the majority of diffusion coefficient measurements are made in the laboratory under controlled conditions. While a number of researchers have used field tracer tests to calculate estimates of in situ diffusion coefficients, care must be taken to quantify all possible sinks for the solute. This can be done through

the use of two tracers, one of which is capable of diffusing into the pore matrix, the other which is not. This performance capability can be obtained based on the physical size characteristics of the tracer particles.

Cathles et al. (1974) used this approach to evaluate matrix diffusion in a fractured igneous rock. They selected 0.5 micrometer diameter silica spheres for the non-diffusing tracer and used sodium chloride for the diffusing tracer. Comparison of the breakthrough concentrations at a pumping well enabled the determination of in situ diffusion coefficients. Care must be taken when using such an approach, however, to ensure that the differences that exist between breakthrough curves are due soley to the diffusive nature of one solute versus the other.

Other examples of field techniques employed to evaluate diffusion coefficients in situ include the method employed by Birgersson and Neretnieks (1983) which was used in the Stripa mine. In this experiment a small diameter borehole was cored in the bottom of a larger borehole in intact granite. The smaller borehole was filled with a solution containing three tracers (Cr-EDTA, Uranine and I^-) and separated from the large borehole by a packer. After a period of six months the intact rock zone surrounding the small diameter borehole was removed by overcoring and analyzed in terms of the solute concentration within the core. The spatial distribution of the tracer within the core as well as the decrease in concentration in the small diameter borehole allowed a diffusion coefficient to be calculated.

In addition to concerns pertaining to the characteristics of the tracer (e.g., non-reactive and non-decaying) care must be exercised to ensure that diffusion is the mechanism responsible for the decrease in solute concentration. That is, convection and dispersion should be verified as being negligible. This may be difficult when using boreholes since by their very nature they are surrounded by an induced

zone of influence, caused by both stress-redistribution and wellbore damage. These effects can be overcome to some extent by allowing the test to run for a sufficiently long time to enable the diffusional front to migrate past the affected zones.

Laboratory values form the vast majority of measurements reported in the literature. Typically these tests consist of a tank of tracer solution and a fresh water tank separated by a section of granite. By monitoring the change in concentration in the two tanks the diffusion rate across the granite specimen can be determined. Errors which may arise in such tests may be associated with the tracer itself (e.g., adsorption, volatility, decay) or the presence of other transport mechanisms or sinks. For example, when high concentrations of solute are being used, density effects may create potential gradients (possibly making advection significant) even though the tanks may be at the same level.

3. PROCEDURES FOR HYDROGEOLOGIC CHARACTERIZATION

In this section, a set of preferred procedures for hydrogeologic characterization of a rock mass for the purpose of quantitatively assessing the performance of an underground nuclear waste repository is outlined. The proposed methods and sequence for data gathering are not an attempt to establish a final assessment of waste emplacement consequences (i.e., dose calculations) but rather they are an attempt to establish the hydrogeologic regime in sufficient detail to allow quantitative input of the hydrogeologic data to such an assessment. The investigative sequence is comprised of a series of steps that pertain to either regional or site characterizations.

3.1 REGIONAL CHARACTERIZATION

Hydrogeologic characterization should be conducted initially at the regional scale since output variables (e.g., pressure distribution) may act as input for the local scale model (e.g., in the form of boundary conditions). Because of the difficulty of obtaining comprehensive field data that are representative of regional conditions, regional studies may be based largely on the concepts of groundwater movement, rather than actual measurements of groundwater systems. The concepts of groundwater movement are typically based on application and solution of the governing partial differential equations. This application requires information on 1) initial and boundary conditions, 2) the state variables (fluid pressure for ground water flow, solute concentration for transport) and 3) the primary hydrogeological parameters (i.e., permeability, porosity, specific storage for groundwater flow).

In the Canadian Shield, the regional flow systems are likely to be bounded by major topographic highs and lows and influenced by geologic conditions. Therefore, characterization of a regional

groundwater flow system in the Shield commences logically with the geologic and structural framework within which a site is located (Figure 3.1). An understanding of the geology is of prime importance, since it provides the basis of our understanding of the physical, mineralogic, and geochemical nature of the rocks within which a regional groundwater flow system exists. Geologic factors that may influence the interpretation of a hydrogeologic flow system include the time and mode of pluton emplacement, sequences of events such as metamorphism, dyke emplacement and diagenesis of recrystallized sediments. Neotectonic conditions, including the state of tectonic stress, major linear discontinuity development and local fracture patterns, form the basis for the conceptualization and eventual interpretation of a regional flow system.

With reference to Figure 3.1, the first step in a regional flow system characterization is to identify approximate hydrogeologic boundaries and to conduct a rough material balance. The hydrogeologic boundaries are identified using geologic, structural, topographic, geomorphologic, hydrologic and paleohydrologic information. The material balance is undertaken assuming a percentage of precipitation as recharge should balance the baseflow (nonrunoff-related) discharge from rivers. Theoretically, it is possible to use such hydrologic data to identify the approximate size of regional flow systems. Verification of the water budgets with actual measurements of baseflow discharge to streams and rivers and direct infiltration measurements using lysimeters or controlled recharge studies, logically follow as the next step in regional hydrogeologic characterization.

Identification and verification of hydrogeologic boundaries are considered one of the most critical aspects of any hydrogeologic investigation. The usual boundaries that require identification and verification are the surface, or water table, boundary, the lateral, or peripheral, boundaries and the basal, or bottom, boundary. In low

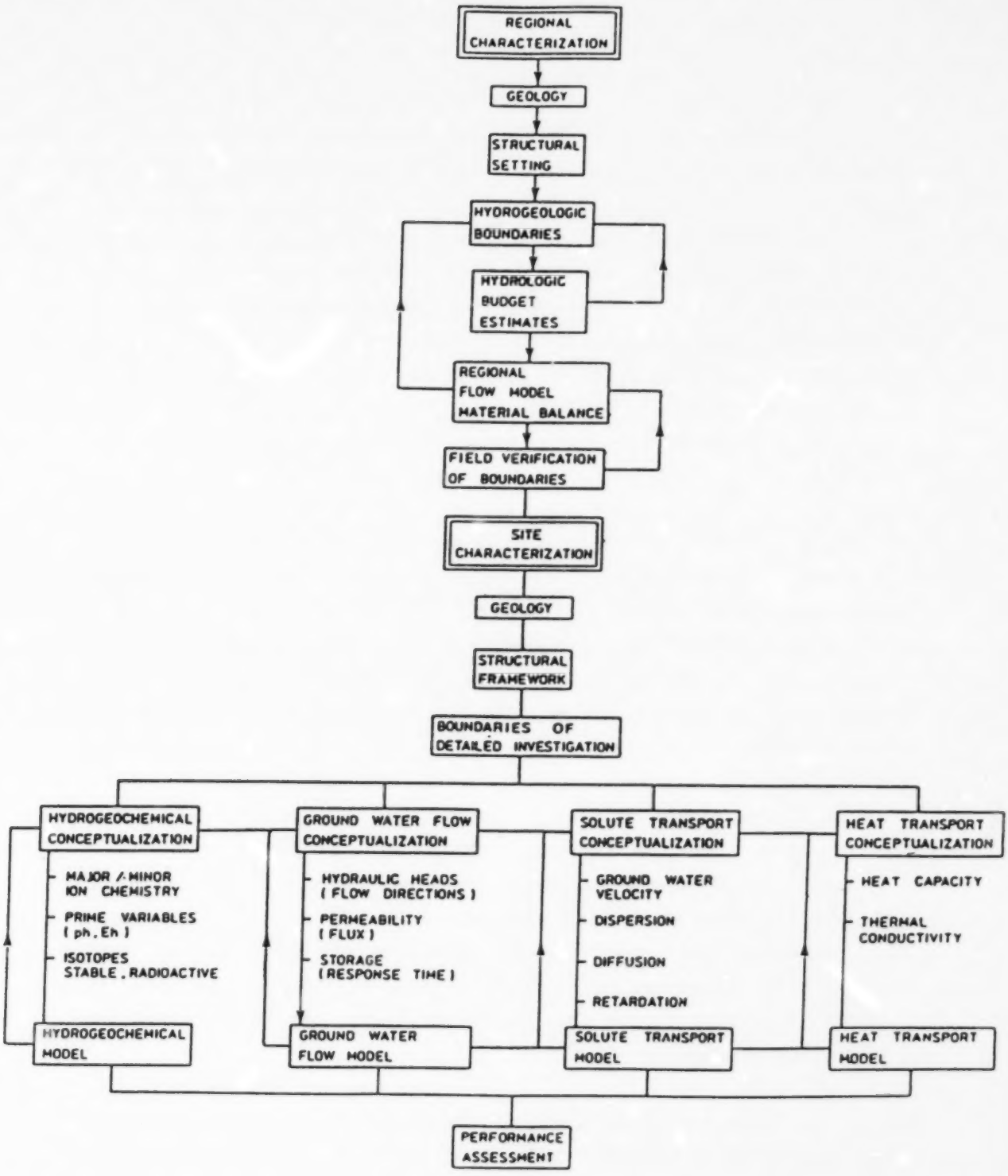

Figure 3.1 Hydrogeologic Methods for Regional and Site Characterization (from GTC, 1985)

permeability systems, it may be necessary to consider the paleohydrology of a site or region as the hydraulic system at depth may not be in equilibrium with current hydrogeologic boundaries.

The water table boundary is perhaps the easiest to identify. In the Canadian Shield, its position is usually a reflection of surface topography. Aerial photographs, topographic maps and some types of remote sensing (thermal infrared) provide additional information on the surface boundary conditions such as the location of potential recharge and discharge areas. Verification of the position of the water table is easily obtained with direct measurments in shallow boreholes and wells.

Lateral or peripheral boundaries of a system are more difficult to verify than the water table. Often, geologic and structural data may guide the selection of peripheral boundaries through the identification of regional scale faults and dykes, etc. Regional-scale remote sensing techniques (Table 3.1) are of use in identifying structural and geologic discontinuites that may behave as hydrogeologic boundaries.

The basal, or bottom, hydrogeologic boundary is the most difficult to identify and verify in a regional-scale hydrogeologic system. The usual assumptions of decreasing permeability with depth that result in an effectively impermeable basal boundary at some depth are generally not applicable to fractured plutonic rocks. High permeability fracture zones which have been observed at depth at several locations in the Canadian Shield, make identification of the lower flow boundary problematic.

Once the hydrogeologic boundaries of the regional system have been approximated and rough hydrologic budget estimates indicate some measure of consistency with the potential recharge/discharge for the area selected, a three-dimensional flow model should be used to

Table 3.1 Remote Sensing Techniques (modified from GTC, 1985)

Method	Information Obtained
Aerial Photoanalysis	General extent of lithologic units, overburden Distribution of major structural discontinuities (faults, fracture zones, etc.)
Aeromagnetic survey	Variations in surficial geology Magnetic anomalies associated with faults
Airborne electromagnetic	Variations in surficial geology Conductors associated with groundwater discharge at faults
Thermal infrared line scanning	Variations in surficial geology Soil moisture variation Structural information in areas with little overburden materials Groundwater discharge zones
Landsat imagery	Structural information on large scale Faults

provide an approximate material balance in the system. The model should incorporate the regional hydrogeologic boundary information, hydrologic budget estimates and use the best available estimates of the primary parameters to describe the internal properties of the model. The final step in regional characterization is to verify the hydrogeologic boundaries of the region. This can be achieved through direct measurement (e.g., exploratory drilling and testing) or by inferences from other hydrogeologic data (i.e., hydrogeochemistry). Completion of regional characterization provides the hydrogeologic framework within which site characterization (drilling, sampling, modeling, etc.) can be most effectively and efficently undertaken. However, it will likely be necessary to alter and iterate both regional or site conceptualizations, with the acquisition, interpretation and assimilation of new data.

3.2 SITE CHARACTERIZATION

Site characterization studies (Figure 3.1) are essentially aimed at providing sufficient quantitative data to undertake performance assessments. As such, the investigations require actual measurements of the hydrogeologic system which can subsequently be interpreted and assimilated using different theoretical approaches and conceptual models. Site characterization studies include measurements at the near-field or repository scale and also at the far-field scale.

The following paragraphs identify a simple step-by-step sequence for characterizing the hydrogeology of a plutonic rock site for performance assessment purposes. Briefly, the sequence consists of the following phases:

1. Preliminary Definition of Site Extent;
2. Surface Characterization;
3. Exploratory Drilling and Testing;
4. Detailed Subsurface Characterization;

5. Specialized Tests;
6. Laboratory Analysis;
7. Development of Groundwater Flow and Solute Transport Models.

Although this sequence of steps has been presented in a more or less chronological order, it should be pointed out that some of these steps may be undertaken concurrently (e.g., exploratory drilling and laboratory analysis) while some should be performed in conjunction with each other (e.g., detailed exploration and development of a groundwater flow model). The rationale for such an approach is the optimization of data collection programs. The following paragraphs discuss each of the steps (and the activities associated with each) in detail.

3.2.1 Preliminary Definition of Site Extent

The first step in any site characterization is the definition of the extent and geometry of system of interest, that is, the development of an original system conceptualization. To a large extent, this conceptualization will be based on information collected as part of the regional characterization. This would include information from remote sensing techniques (see Table 3.1) as well as topographic maps. This information would be used to identify geological and hydrological controls that could serve as boundaries for the local groundwater flow system. Such controls are essential in the development of any model of the groundwater system at the site.

Remote sensing techniques will also play a major role in the initial selection of the site. Part of the criteria used in the site selection process will be based on information which can be obtained from remote sensing techniques. This information would include:

- Extent of lithologic units (e.g., batholith);
- Definition of surface geology (e.g., overburden);
- Large scale structural information (e.g., faults, lineaments);
- Existence of discharge zones.

3.2.2 Surface Characterization

The next step in the site characterization process is the undertaking of a data collection program using surficial investigation methods. The objectives of this program are multifold and include the verification of data obtained (or inferred) from remote sensing methods as well as the collection of preliminary geological structural and fracture data. The major surficial investigation methods are presented in Table 3.2, and consist primarily of geophysical surveys, geologic and fracture mapping and sampling of spring discharges. These activities are aimed at the definition of lithologies, extent of the pluton, and geometry of the fracture system (both small scale fractures and large scale faults/lineaments). Surface fracture mapping should include the definition of both fracture and infilling characteristics including the orientation, length and distribution of fractures as well as the chemical composition and description of infilling materials.

In addition to the surface mapping and surface geophysical surveys, this phase should also include shallow augering and trenching for the purposes of defining the extent and nature of the overburden. Characterization of the overburden is also important at this point since its extent and nature will impact the interpretation of surface geophysical surveys. This phase may also involve the installation of piezometers in the overburden depending on the extent of these materials. Any piezometers that are installed should have water levels measured periodically (at least once per month) and should be sampled for chemical analyses.

Table 3.2 Surficial Investigation Methods (modified from GTC, 1985)

Method	Information Obtained
Seismic survey	Formation depths and thicknesses Depth to crystalline rock surface In some instances subhorizontal structures.
Gravity survey	Structural Depth to crystalline rock surface
Sampling of spring discharges	Hydrogeochemical
Electromagnetic	Structural
Resistivity	Formation depths and thicknesses
Mapping outcrops	Structural, lithologic Fracture zone data

The information resulting from this phase will serve to confirm existing data (thereby providing a measure of its reliability) as well as provide new data. The newly acquired data should be incorporated into the original conceptualization of the site developed under Step 1 and may necessitate revising the system boundaries originally proposed.

3.2.3 Exploratory Drilling and Testing

The purposes of this step are both to confirm the developing conceptualization of the site and to provide additional information which will serve as a guide in the planning/development of a detailed drilling/exploration program. More specifically the boreholes are intended to provide general geologic and hydrogeologic information on the site such as pluton depth, geometry of major faults/lineaments intensity of fracturing and approximate hydraulic conductivities and hydraulic heads.

The boreholes drilled as part of this phase would be few in number but should be cored to maximize the information return. Boreholes drilled in an exploratory program should be both vertical and inclined to ensure representative (unbiased) sampling of subsurface conditions. These boreholes, like those conducted under the detailed subsurface characterization program, should adopt certain procedures to ensure the resulting data is reliable and representative. This would include, for example, the implementation of a drill water tracing system. This would enable the presence of drill water in groundwater samples to be ascertained (i.e., providing an indication of contamination). It is also recommended that some through-the-bit (TTB) testing be conducted during drilling to provide rough estimates of hydraulic heads and permeabilities. This technique is useful in that it provides an early indication of the existence of open faults and fracture zones. This may also be observed by monitoring of drilling fluid return. Other activities which should take place during the

borehole drilling program include lithologic and structural (using oriented core) core logging and the collection of representative pressurized groundwater samples. Field monitoring of pH, Eh (the latter by a number of different electrode methods), temperature electrical conductance and drill water tracer concentrations during the groundwater sampling is also required.

Upon completion of the drilling, significant data will have been collected. This includes, for example, borehole directional information provided by gyroscopic surveys, fracture information (location, orientation, size) obtained from televiewer and T.V. logs and various other information provided by standard and more esoteric geophysical logs. It should be noted that borehole geophysical methods, while useful for confirmatory efforts, do not provide the quantitative data necessary for performance assessment purposes.

A complete suite of borehole investigative techniques is presented in Table 3.3. Hydrogeologic reconnaissance logging (also known as straddle packer testing) should be conducted relatively quickly after drilling. While such open-borehole permeability profiling yields less reliable permeability numbers than TTB testing, it is useful since it identifies the location of important high or low permeability discontinuities in a rock mass. The exact location of these discontinuities is important for design of longer term monitoring equipment and reduces the uncertainty in subsequent fluid potential measurements in long test intervals.

After the completion of open-borehole activities the borehole should be cased as soon as possible. The purpose of this is to reduce the quantity of cross-flow between various fracture zones and to minimize borehole history effects. The holes should be cased using a system that has the capability of monitoring several zones such as "Westbay" casing or other multiple piezometer/packer completions. Once the casing has been installed, an initial series of pressure

Table 3.3 Borehole Investigation Methods (modified from GTC, 1985)

Borehole Investigation Method	Information Obtained
Drill Core	Rock types Fracture orientation Geological/mineralogical data Fracture infilling minerals
Overcore stress testing	2-d and 3-d state of stress
Drill fluid logging	Formation gases Fluid gains/losses at permeable zones (e.g., fracture zones)
Hydraulic tests - drill stem tests - pulse tests - slug tests - constant head tests - injection or pumping tests (constant or variable rate) - cross-hole interference	Hydraulic conductivity Identification of fracture zones, permeable zones and lower permeability zones In situ formation pressure (in some cases)
Hydrogeologic reconnaissance log (hydraulic tests)	Hydraulic conductivity profile of borehole
Labelled slug test	Flow rates in borehole Inflow/outflow zones
Fluid logging	Inflow/outflow zones
Spinner and heat pulse flowmeter tests	Flow rates in borehole Inflow/outflow zones
Tracer tests	Fracture interconnectivity Fluid velocity Porosity estimate
Self Potential (Spontaneous) log	Formation water properties Lithology
High resolution dipmeter	Formation dip and direction Stratigraphic interpretation Hole geometry
Electromagnetic propagation log	Porosity variation

Table 3.3 (cont'd)

Borehole Investigation Method	Information Obtained
Resistivity logs	Lithology Drilling fluid invasion
Cross-hole electrical	Fracture zones
Density	Porosity; lithology
Neutron	Porosity; lithology
Sonic	Fracture location
Long-spaced sonic	Porosity; lithology Fracture location
Natural gamma ray	Lithology
High resolution temperature log	Geothermal gradient Inflow/outflow zones
Continuous directional survey	Azimuth and deviation from vertical of borehole
Sidewall sampler	Samples from wall of borehole
Caliper log	Hole size information
Borehole geometry tool	Hole size information
Sonic televiewer log	Fracture orientation
Impression packer	Fracture orientation
Tube wave	Fracture location
TV log	Fracture frequency and indication of whether open or closed
Geomechanical tests	Rock and fracture compressibility
Hydraulic Fracturing	3-d state of stress
Downhole geochemical probe	Eh pH Fluid conductivity Temperature
Multipacker pressure measurement system	Formation pressures at various depths

measurements should be made. Following initial pressure measurements, further groundwater sampling and hydraulic conductivity testing can be undertaken using the casing completions. At this stage, long term pumping for larger-scale hydraulic conductivity evaluation and collection of representative groundwater samples can be performed more economically than during drilling (i.e., no excessive drill rig stand by costs). Following sampling and testing, a comprehensive pressure monitoring program with monthly pressure measurements should be implemented.

The reliability of the measurements made with any casing system should be assessed by repeat measurements and integrity checks of isolating packers. It should also be noted that uncertainty of the fluid potential increases with length of monitoring interval, so an effort should be made to keep the intervals relatively short. Overall reliability of measurements can be evaluated by comparison of through-the-bit and multiple-packer monitoring measurements and consistency of potential distribution with permeability distribution (i.e., high k zones should show low potential gradient).

The information obtained from the exploratory drilling program should be used in updating the conceptualization of the site as well as planning the location of boreholes of the detailed subsurface characterization program.

3.2.4 Detailed Subsurface Characterization

The boreholes drilled as part of the detailed subsurface characterization program should be targeted to areas where better definition of site characteristics is required. These characteristics may include both structural (e.g., fault/lineament extent) and hydrogeological features (e.g., location of discharge/recharge zones). The techniques proposed for the exploratory drilling program (e.g., use of drill water tracers, collection of geochemical samples) should also

be followed where possible in the detailed program. It should be noted that although cored holes are recommended for the exploratory program, it may not be feasible (from a financial standpoint), or even necessary, to use only cored holes in this phase. A mix of cored and percussion drilled holes is probably adequate for most detailed site investigation programs.

Whatever the techniques used to collect geologic, structural and hydrogeologic data, it is essential to ensure that the data are reliable, representative and to be aware of any biases that may be induced through the measurement technique. For example, the reliability and representativeness of the structural and hydrogeologic conditions of a rock mass developed from remote, surficial and borehole investigations is affected by certain investigative biases. The biases include the bias of most remote sensing methods to identify near vertical structures and the bias of boreholes to intersect structures oriented normal to the borehole axis. Because most surface boreholes are, for logistical reasons, drilled near vertical, the results of most surface drilling programs only poorly sample the near vertical structures in a rock mass. This shortcoming can be particularly important, if for certain reasons such as thick overburden cover, remote sensing and surficial investigative techniques do not provide reliable information on the existence of subvertical structural discontinuities. In two case studies (Raven, 1986; Davison, 1985) where overburden thickness was of minor importance and most surface boreholes were drilled vertically, subvertical high permeability fractures were found to exist only after completion of detailed hydrogeologic investigations. The results of these case studies are important because they represent two of the most detailed hydrogeologic characterizations completed in fractured crystalline rock in Canada and they demonstrate the sampling bias associated with vertical boreholes. This sampling bias can be reduced and the reliability of the subsurface structural framework enhanced by the use of inclined boreholes. The

historical preference for near vertical exploratory boreholes relates primarily to the relative ease of drilling, testing and monitoring in such boreholes. However, because vertical high permeability fractures may provide a direct solute transport pathway from a waste repository to surface it is essential that these structural discontinuities be identified and hydrogeologically characterized.

The reliability of borehole permeability measurements can be evaluated from comparison of test results obtained during the different testing phases identified above and indirectly under other borehole methods. For example, high resolution temperature logging, and borehole flow meter surveys can provide corroborating evidence of the location and magnitude of flow associated with zones of fluid inflow and outflow in an open borehole.

The results of the detailed borehole exploration program will be used to continuously update the conceptualization of the site. As new information is acquired the focus of the detailed exploration program may also change.

3.2.5 Specialized Tests

This section is meant to describe a number of specialized tests which are typically conducted after the completion of the detailed investigation program. They include such tests as: large scale pumping tests, tracer tests, in situ diffusion and stress measurements. There are a number of reasons why most of these tests are conducted after the completion of the detailed investigation. Large scale pumping interference and tracer tests typically require a good understanding of the geology, structural and hydraulic features of a site to ensure maximum probability of the successful completion and interpretation of the test. Tracer experiments should be conducted under natural gradient conditions (if possible) in both single and multiple fracture systems under a variety of scales. The reliability

of groundwater velocity estimates obtained from natural gradient tests can be obtained by comparison with the "ages" of groundwater determined from their isotopic compositions. Tracer tests are useful in determining both a flow porosity and a dispersivity. Large scale pumping tests are difficult to evaluate accurately in fractured crystalline rocks since the analysis may be highly sensitive to the flow field geometry and the existence of boundaries (e.g., as determined by the areal extent of the fractures). An accurate understanding of the fracture network is therefore essential to the correct interpretation of these tests.

In situ diffusion tests are conducted for the purpose of evaluating matrix diffusion coefficients. As such, these tests require long test times and an unperturbed system. The reliability of the matrix diffusion parameter determined from the above test can be evaluated through the comparison of the results of long term tracer migration experiments in single fractures, and laboratory diffusion experiments performed under in situ stress, temperature and chemical conditions.

Because fluid flow through fractures is known to be highly stress dependent, it is very important to define the regional and site specific states of tectonic stress. Typically, the two dimensional and three dimensional states of stress can be determined from overcore stress measurements and hydraulic fracturing techniques. Data on stress measurements in the rock mass are useful in interpreting both site and regional structural conditions, existing fracture characteristics and possibly permeability anisotropy resulting from stress anisotropy. As such, borehole stress measurements may refine or alter both regional and site geologic and structural conceptualizations.

3.2.6 Laboratory Analyses

Laboratory analyses may be conducted at any time during or after the field investigation programs. Laboratory analyses are conducted on either samples of groundwater or rock. Groundwater samples are typically analyzed for environmental and radioactive isotopes, major ions, trace elements, rare earth metals and dissolved gases. In addition, fluid samples are usually subjected to viscosity and density measurements.

The majority of useful rock property data resulting from laboratory analysis is performed on intact and fractured cores. From a hydrogeologic viewpoint, this would include permeability, porosity and effective solute diffusivities for both weathered and unweathered cores. The variation of these properties as a function of other variables (e.g., stress, temperature) should also be evaluated. Porosities and effective diffusivities should also be determined for infilling materials. In addition to hydrogeologic tests, the cores should also be evaluated in terms of their thermal (e.g., heat capacity, thermal conductivity) and mechanical (e.g., Poisons ratio, bulk moduli) properties. Both the cores and infilling material should undergo mineralogical and chemical (major elements, isotopes) analyses. Lastly, chemical retardation experiments should be conducted for radionuclides in natural fracture samples under representative chemical conditions.

In any laboratory test program aimed at measurement of parameters that may be extrapolated to field situations, it is necessary to determine if sampling or scale effects are important. This typically requires evaluation of material properties or parameters on different sized samples.

3.2.7 Development of Groundwater Flow and Solute Transport Models

The data obtained from the field and laboratory analyses should be integrated into a three-dimensional model that is capable of representing the physics of the groundwater flow system. A sufficient amount of data would be incorporated into the model to adequately characterize the site. The model must be capable of representing both groundwater flow and solute transport processes. The model should be developed in conjunction with the data collection program and could be used to identify areas where further data collection is required. As such the model can be used to perform sensitivity analysis to identify those parameters/assumptions that dominate the flow regime.

The model should also be validated, that is, not all of the available data is to be used in the calibration of the model but some should be used to test the models predictive capability, preferably over a large portion of the site.

The reliability of the field data and the system conceptualization can be further assessed by comparing field fluid potential distributions with model-derived potential distributions under steady and transient conditions and by comparing geochemical and isotropic characteristics of groundwater with evolutionary flow paths defined by the model. Validation of the developed model can specifically be evaluated using long-term, large-scale hydraulic perturbations (e.g., excavation, pumping) and tracer migration experiments.

4. SUMMARY

This report identifies the hydrogeologic factors that should be addressed for performance assessment of a radioactive waste disposal facility in plutonic rock. The hydrogeologic factors identified in this report are broadly grouped into three categories:

- theoretical methods or conceptual approaches;
- groundwater flow factors; and
- solute transport parameters.

In the theoretical methods section, the various theoretical and conceptual approaches for evaluating the physical hydrogeologic conditions of plutonic rock are identified and evaluated with respect to data requirements, applications and limitations. In the groundwater flow factors and physical solute transport parameters sections, the factors and parameters controlling fluid flow and solute transport in plutonic rock are identified. For each hydrogeologic parameter and factor, we assess why it is important, at what scale it should be measured, how it can be measured and what current methods and techniques are most suited to its reliable measurement.

In the final section of the report, we recommended a set of procedures for reliable hydrogeologic characterization of a plutonic rock mass for waste isolation purposes. This characterization included both regional and site-scale characterizations. Table 4.1 presents a table summarizing the approaches and activities recommended for inclusion in disposal guidelines.

It should be stressed that the recommended set of procedures are based on the techniques and methods that are currently available. In completing this study, a significant gap was perceived between proven investigative methods for groundwater flow and solute transport in plutonic rock and the characterization and understanding required to

Table 4.1 Summary of Factors to be Considered in Disposal Guidelines

Area of Concern	Purpose	Factors	Possible Approach
Regional Characterization	- Provide boundary conditions for site analyses that are consistent with regional flow field	- Theoretical method	- Equivalent porous media model
		- Flow system geometry and boundary conditions	- Use existing information regarding structural geologic framework and know water levels (e.g., lakes)
	- Define areal extent of site investigations	- Hydraulic conductivity	- Existing values
	- Identify areas that require additional data collection; i.e., those areas to which the groundwater flow regime demonstrate a high sensitivity and possess high uncertainty	- Specific storage	- Existing values
		- Fluid potential	- Observed surface water and existing groundwater levels and density information
Site Characterization	- Provide accurate groundwater flux information to allow calculation of radionuclide release rates (e.g., leach, corrosion, dissolution rates)	- Theoretical method	- Equivalent porous media considering coupled processes and REV constraints
		- Flow system geometry	- Detailed field investigation
	- Define likely pathways	- Boundary conditions	- Obtain from regional model
	- Determine travel times along pathway	- Hydraulic conductivity	- Pulse, slug, pump tests
	- Estimate concentrations at biosphere discharge points	- Specific storage	- Evaluate components
		- Fluid potential	- Piezometers, hydraulic profiling as part of detailed site investigation
		- Groundwater velocity	- Tracer test
		- Dispersion	- Tracer test
		- Diffusion	- Laboratory/field experiments

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evaluate the performance of a nuclear waste storage facility. Much of this gap can be attributed to the relatively recent need to understand the hydrogeology of low permeability rocks. Traditionally, hydrogeologic study was focussed primarily on the the flow and, to a lesser extent, solute transport properties of granular unconsolidated media. The study of safe disposal of nuclear waste in low permeability plutonic rocks has created a relatively new hydrogeologic discipline concerned not so much with groundwater supply but with evaluation of the isolation capability provided by such formations.

Because the study of groundwater flow and solute transport in low permeability rocks is relatively recent, most of the available theoretical methods, conceptual approaches and investigative techniques were developed with minor modification from studies undertaken in more permeable porous media. As explained below, the applicability of such methods, approaches and techniques to waste disposal problems in low permeability plutonic rocks remains largely unproven.

One of the major concerns with any theoretical method or conceptualization is the manner in which spatial variability (heterogeneity) in material properties is incorporated into a hydrogeologic evaluation. This concern is particularly relevant in plutonic rocks where variations in the degree and extent of fracturing can be expected to introduce significant, and likely unknown, heterogeneities in hydrogeologic properties. One method of dealing with such heterogeneity is to assume an equivalent porous media approach and through the use of appropriately sized samples, the heterogeneities are effectively averaged. Such a deterministic approach is thought to be applicable to large or regional hydrogeologic scales where it is impossible to know all heterogeneities. However, the validity of such an approach is difficult to assess and does not explicitly quantify the effect of spatial variability of material properties on a hydrogeologic evaluation. An alternate theoretical approach is to characterize spatial variability and uncertainty using

probabilistic methods. While such methods have a clear and preferred advantage over deterministic methods, the required data bases (e.g., probability distribution functions for material properties) are currently not available and for most large or regional-scale problems may not be obtainable. Furthermore, it is generally not known at what spatial scales different hydrogeologic properties of plutonic rock can be assumed to be statistically homogeneous and ergodic. While we believe that probabilistic methods may be the only feasible alternative to incorporating spatial variability, it is clear that much work remains to be done and that use of any theoretical method (such as those discussed in this report) requires substantiating geologic and hydrogeologic evidence that the method is capable of describing observed behavior.

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GLOSSARY OF TERMS

Adsorption	The attachment of an aqueous chemical species to a solid. The attachment may be by an addition or replacment reaction. It may be either physical, designated by a low dependence of the rate of reaction on temperature, or chemical, designated by a high dependence of the rate on temperature.
Advection	To transport solute or energy concurrently with the soil water or groundwater, synonomous with convection.
Anisotropic Medium	A porous medium having directionally dependent properties (e.g., hydraulic conductivity).
Aperture	A measure of the size of opening or silt representative of the void space of a fractured medium.
Aquifer	A formation containing sufficient saturated permeable material to yield significant quantities of water to wells and springs.
Borehole Skin	A term developed in the petroleum literature describing a thin layer of material surrounding a borehole and possessing permeability different than that of the formation.
Brownian Motion	The irregular zigzag movement of extremely minute particles suspended in a liquid.
Capillarity	The property of tubes with hairlike openings when immersed in a fluid to raise (or depress) the fluid in the tubes above (or below) the surface of the fluid in which they are immersed.
Capillary Fringe	The zone immediately above the water table in which water is held above the water table by capillarity.
Compressibility	A material property describing the change in volume or strain induced in a material under an applied stress.
Conduction	Transmission through or by means of a conductor. Distinguished, in the case of energy, from advection and dispersion.
Confined Aquifer	An aquifer bounded above and below by impervious formations.

Consolidation	The process by which the volume occupied by solid porous medium reduces when the effective stress borne by the media increases.
Convection	To transport solute or energy concurrently with the soil water or groundwater, synonomous with advection.
Diffusion	A molecular level process that spreads solute in water as a result of Brownian motion of water molecules.
Dispersion (Mechanical)	Refers to the velocity driven component of hydrodynamic and consists of the product of the groundwater velocity and a coefficient known as dispersivity.
Dispersivity	A coefficient used to relate mechanical dispersion to interstitial groundwater velocity.
Distribution Coefficient	A coefficient representing the partitioning of a groundwater contaminant between liquid and solid phases.
Effective Porosity	The amount of interconnected pore space available for fluid flow expressed as a ratio of interstical volume to total volume, also kinematic porosity.
Equilibrium	The state of a system that is thermodynamically the most stable at a given temperature, pressure, and elemental composition.
Equilibrium Water Saturation	The percent of water filled porosity corresponding to first appearance of a continuous water phase.
Evaporation	The net transfer of water from the liquid phase to the vapour phase.
Evapotranspiration	A combination of the evaporation and transpiration processes.
Fickian Transport or Process	Transport or flux of a solute as a result of Fick's law for molecular diffusion or an analogy applying Fick's law to processes other than diffusion.
Field Capacity	Water content remaining in a unit volume of soil after drainage resulting from gravity, does not represent an intrinsic soil property since gravity drainage continues indefinitely.

Flow Path Tortuosity	The nonstraight nature of soil pores.
Fracture System	A medium where the connected porosity transmitting groundwater is characterized as fractures or fissures.
Free Water Surface	The upper surface of groundwater or that level in the ground where the water is at atmospheric pressure; also water table; also phreatic surface.
Gradient	Change in dependent variable per unit change in spatial or temporal independent variable.
Gravitational Potential	The difference in elevation between the point of interest and a reference point or plane.
Hydration	The process of clustering ions of unlike charge and incorporating water molecules in loosely bound complexes.
Hydraulic Conductivity	The proportionality factor in Darcy's law as applied to the viscous flow of water in soil (i.e., the flux of water per unit gradient of hydraulic potential).
Hydrodynamic Dispersion	The process by which solute spreading occurs on a macroscopic scale due to mechanical and molecular mixing.
Hysteresis	The loop in the moisture content versus matric potential curve defined by the retention (drying) and imbibition (wetting) curves.
Imbibition	To wet or imbibe the soil profile.
Immiscible Displacement	Displacement of one fluid by another.
Infiltration	The downward entry of water into the soil.
Intrinsic Permeability	The property of a rock or soil defining its ability to transmit a fluid.
Ion Exchange	The process of exchanging two ions on an adsorption site.
Isotropic	Independent of direction, used to describe properties of the porous medium (e.g., hydraulic conductivity).

Kinematic Pathline	The path of solute in an aquifer that is determined strictly by the pore water path and velocity.
Kinematic Porosity	The volume of flowing water per unit bulk volume of porous medium, also effective porosity.
Kinetics	A term to designate dynamic chemical changes toward the state of chemical equilibrium.
Mass Flux	Rate of transfer of mass across a surface.
Nonequilibrium	A state of a system that is not thermodynamically the most stable.
Peclet Number	A nondimensional quantity defining the relative importance of advection in comparison to diffusion or diffusion-type dispersion.
Pellicular Water	Water adhering as films to the surfaces of openings and occurring as wedge-shaped bodies at junctures of interstices in the zone of aeration above the capillary fringe.
Permeability	see intrinsic permeability.
Phreatic Aquifer	An aquifer bounded below by an impermeable formation and above by the free water surface.
Pluton	A body of igneous rock that has formed beneath the surface of the earth by consolidation from magma.
Pore	An interstice or void. A space in rock or soil not occupied by solid mineral matter.
Porosity	The ratio of the volume of voids to the total volume of porous media.
Porous Media, Medium	A physical environment containing voids, pores, interstices, or other openings that may or may not interconnect.
Potentiometric Head	The height of a surface to which water in an aquifer would rise by hydrostatic pressure.
Reactive Solute	A solute that reacts with the medium by any of a number of processes.
Recharge	The quantity of water or the process by which water is added to the zone of saturation.

Relative Saturation	The ratio of water-filled pore volume to total pore volume.
Retardation Factor	The reciprocal of the retarded solute velocity of the groundwater (i.e., reciprocal of relative velocity).
Saturation (water)	The total water that can be absorbed by water-bearing materials without dilation of the sediments.
Soil Matrix	The unconsolidated mineral material comprising a major portion of, if not the entire, vadose zone.
Soil Water Potential	The amount of work a unit quantity of water in an equilibrium soil-water system is capable of doing when it moves to a pool of water in the reference state of the same temperature.
Solute	The chemical species appearing as a dissolved constituent in soil water or groundwater.
Specific Retention	The volume of water per unit area of soil retained by a soil column.
Specific Storage	The volume of water that a unit volume of a formation releases from storage due to a unit decline in head.
Specific Yield	The volume of water per unit area of soil released by a soil column, extending from land surface to free water surface, when the water table is lowered one unit depth.
Storativity	The volume of water that a unit area of an aquifer releases from storage for a unit decline in head.
Thermal expansivity	A material property describing the volumetric change resulting from changes in temperature.
Transmissivity	The flow of water through a unit width of aquifer under a hydraulic gradient of one equal to the product of hydraulic conductivity and aquifer thickness (for a saturated confined aquifer).
Transpiration	The process by which plants remove moisture from the soil and release it to the atmosphere as vapour.

Unsaturated System	That portion of the subsurface geology where the porosity is shared by water and air, and the matric potential is nonzero (i.e., the water content of the soil profile is less than saturation).
Vadose Water	Water in excess of pellicular water seeping toward the water table; used in this text as a synonym for gravity water.
Viscosity, Coefficient of	The amount of force necessary to maintain a unit difference in velocity between two layers of water a unit distance apart.
Void Ratio	Ratio of void volume to solid volume.
Water Table	In pervious granular material the water table is the upper surface of the body of free water which completely fills all openings in material sufficiently pervious to permit percolation. In fractured impervious rocks and in solution openings it is the surface at the contact between the water body in the openings and the overlying ground air.